

# The Exotic $XYZ$ Charmonium-like Mesons

STEPHEN GODFREY

*Ottawa-Carleton Institute for Physics*

*Department of Physics, Carleton University, Ottawa, Canada K1S 5B6*

STEPHEN L. OLSEN

*Institute of High Energy Physics, Beijing, 100049 China, and*

*Department of Physics & Astronomy*

*University of Hawaii at Manoa, Honolulu, Hawaii, 96822, U.S.A.*

**Key Words** Mesons, Charmonium, Hybrids, Molecules, Tetraquarks

**Abstract** Charmonium, the spectroscopy of  $c\bar{c}$  mesons, has recently enjoyed a renaissance with the discovery of several missing states and a number of unexpected charmonium-like resonances. The discovery of these new states has been made possible by the extremely large data samples made available by the  $B$ -factories at the Stanford Linear Accelerator Center and at KEK in Japan, and at the CESR  $e^+e^-$  collider at Cornell. Conventional  $c\bar{c}$  states are well described by quark potential models. However, many of these newly discovered charmonium-like mesons do not seem to fit into the conventional  $c\bar{c}$  spectrum. There is growing evidence that at least some of these new states are *exotic*, *i.e.* new forms of hadronic matter such as mesonic-molecules, tetraquarks, and/or hybrid mesons. In this review we describe expectations for the properties of conventional charmonium states and the predictions for molecules, tetraquarks and hybrids and the various processes that can be used to produce them. We examine the evidence for the new candidate exotic mesons, possible explanations, and experimental measurements that might shed further light on the nature these states.

## CONTENTS

Introduction . . . . .	2
Theoretical Background . . . . .	3
<i>Charmonium states and properties</i> . . . . .	3
<i>Multiquark states</i> . . . . .	6
<i>Charmonium hybrids</i> . . . . .	7
<i>Threshold effects</i> . . . . .	8
Experimental Background . . . . .	8
Experimental evidence and theoretical interpretations for the $XYZ$ mesons . . . .	10
<i><math>X(3872)</math></i> . . . . .	10
<i><math>XYZ</math> particles with <math>mc^2</math> near 3940 MeV</i> . . . . .	13
<i>The <math>J^{PC} = 1^{--}</math> states produced via ISR</i> . . . . .	15
<i>The <math>Z^+(4430) \rightarrow \pi^+\psi'</math></i> . . . . .	18
<i>Are there corresponding states in the <math>s</math> and <math>b</math> quark sectors?</i> . . . . .	19

<i>Summary</i> . . . . .	21
--------------------------	----

## 1 Introduction

In 1964, faced with a large proliferation of strongly interacting subatomic particles, Murray Gell-Mann (1) and, independently, George Zweig (2) hypothesized the existence of three fractionally charged constituent fermions called "quarks," the charge =  $+2/3e$  up-quark ( $u$ ) and the charge =  $-1/3e$  down- ( $d$ ) and strange- ( $s$ ) quarks and their antiparticles ( $e = +1.6 \times 10^{-19}$  Coulombs). In the Gell-Mann Zweig scheme, mesons are formed from quark and antiquark ( $q\bar{q}$ ) pairs<sup>1</sup> and baryons from three-quark triplets ( $qqq$ )<sup>2</sup>. This picture was remarkably successful; it accounted for all of the known hadrons at that time and predicted the existence of additional hadrons that were subsequently discovered.

Now, over forty years later, the Gell-Mann Zweig idea, currently known as the "Constituent Quark Model" (CQM),<sup>3</sup> remains an effective scheme for classifying all of the known hadrons, although the number of quarks has expanded to include the charge =  $+2/3e$  charmed- ( $c$ ) and top- ( $t$ ) quarks and the charge =  $-1/3e$  bottom- ( $b$ ) quark.

Our current understanding is that the forces that bind quarks into hadrons are described by the non-abelian field theory called Quantum Chromodynamics (QCD)<sup>4</sup>. At distance scales that correspond to the separations between quarks inside hadrons, QCD is a strongly coupled theory and perturbation theory is of limited applicability. It is expected that ultimately, numerical lattice QCD computations (3) will generate predictions for QCD observables such as masses, transitions, decays, etc. However, progress, while steady, is slow, and it will be some time before the predictions are able to make precise reliable predictions for excited charmonium states.<sup>5</sup> To date, models that incorporate general features of the QCD theory have proven to be most useful for describing the spectra and properties of hadrons. A prediction of these QCD-motivated models, supported by lattice QCD, is the existence of hadrons with more complex substructures than the simple  $q\bar{q}$  mesons and the  $qqq$  baryons. However, in spite of considerable experimental effort, no unambiguous evidence for hadrons with a non-CQM-like structure has been found, at least not until recently, when studies of the spectrum of charmonium mesons, *i.e.* mesons formed from a  $c\bar{c}$  pair, have uncovered a number of meson candidates that do not seem to conform to CQM expectations. The status of these candidate non- $q\bar{q}$  particles, the so-called  $XYZ$  mesons, is the subject of this review, which is organized as follows: Section 2 provides a brief summary of theoretical expectations for charmonium mesons and the more complex structures that are expected in the context of QCD; Section 3 provides

---

<sup>1</sup>Meson: a bound state of a quark and antiquark ( $q\bar{q}$ )

<sup>2</sup>Baryon: a bound state of three quarks ( $qqq$ )

<sup>3</sup>CQM: constituent quark model

<sup>4</sup>QCD: Quantum Chromodynamics, the theory of the strong interactions

<sup>5</sup>Lattice QCD: A numerical approach to calculate hadronic properties. In the lattice approach space-time is discretized and observables are typically calculated using Monte Carlo techniques used to calculate expectation values of various operators by integrating over the quark gluon configurations.

some experimental background of the recent observations; Section 4 forms the bulk of the review, describing the evidence for and measured properties of the  $XYZ$  states, why they defy any CQM assignment, and theoretical speculation about their nature and how to test these hypotheses. Summary points and future issues are given in Section 5. Recent related reviews on charmonium spectroscopy and the  $XYZ$  states are given in Refs. (4, 5, 6, 7).

## 2 Theoretical Background

QCD-motivated potential models successfully described the  $J/\psi$  and  $\psi'$  as  $c\bar{c}$  states soon after they were discovered more than thirty years ago. These models have stood up quite well over the ensuing years, during which time other low-lying  $c\bar{c}$  states were discovered and found to have properties that agree reasonably well with the models' predictions. Early pioneering papers also predicted the existence of mesons that are more complicated than conventional  $q\bar{q}$  states such as multiquark states (8, 9)<sup>6</sup> and hybrid mesons, states with an excited gluonic degree of freedom (10)<sup>7</sup>. While corresponding *exotic* states are predicted to exist in the light meson spectrum, there they are difficult to disentangle from the dense background of conventional states (11). The charmonium spectrum provides a cleaner environment where one might hope that non-conventional states containing  $c\bar{c}$  pairs would be easier to identify. In this section we give a brief overview of the properties of conventional charmonium states and the non-conventional multiquark and hybrid states. In addition, we mention threshold effects that could masquerade as resonances.

### 2.1 Charmonium states and properties

In QCD-motivated quark potential models, quarkonium states are described as a quark-antiquark pair bound by an inter-quark force with a short-distance behavior dominated by single-gluon-exchange and, thus, approximately Coulombic, plus a linearly increasing confining potential that dominates at large separations. Typically, the energy levels are found by solving a non-relativistic Schrödinger equation, although there are more sophisticated calculations that take into account relativistic corrections and other effects. These give energy levels that are characterized by the radial quantum number  $n$  and the relative orbital angular momentum between the quark and antiquark,  $L$ . The current status of this approach is shown in Fig. 1, where the charmonium levels are shown. For those levels that have been assigned, the commonly used name of its associated meson is indicated.

The orbital levels are labeled by  $S$ ,  $P$ ,  $D$ , ... corresponding to  $L = 0, 1, 2, \dots$ . The quark and antiquark spins couple to give the total spin  $S = 0$  (spin-singlet) or  $S = 1$  (spin-triplet).  $S$  and  $L$  couple to give the total angular momentum of the state,  $J$ . The parity of a quark-antiquark state with orbital angular momentum  $L$

---

<sup>6</sup>Multiquark state: a state that has more quark or antiquark content than conventional  $q\bar{q}$  mesons and  $qqq$  baryons

<sup>7</sup>Hybrid meson: a meson with an excited gluonic degree of freedom

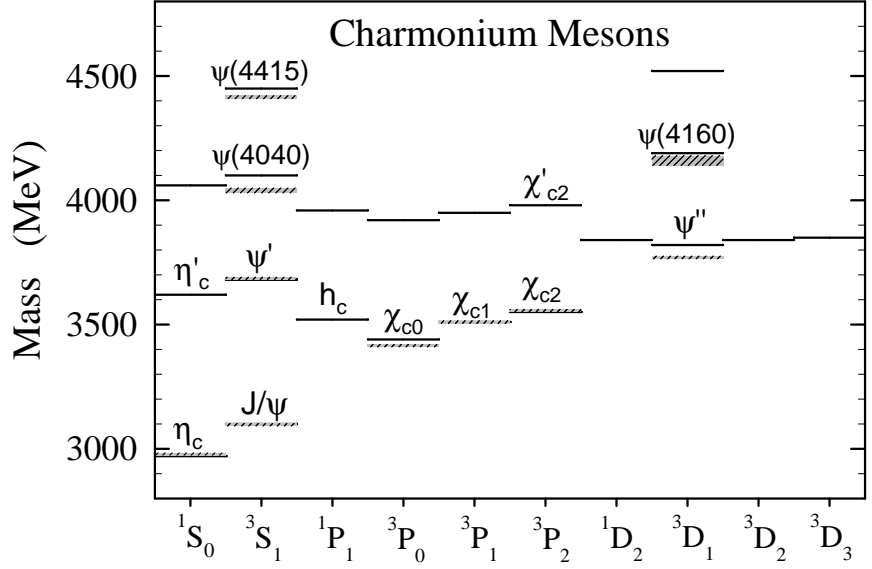


Figure 1: The charmonium level diagram. The commonly used names for the mesons associated with assigned states are indicated.

is  $P = (-1)^{L+1}$  and the charge conjugation eigenvalue is given by  $C = (-1)^{L+S}$ . Quarkonium states are generally denoted by  $^{2S+1}L_J$  with quantum numbers  $J^{PC}$ . Thus, the  $L = 0$  states are  $^1S_0$  and  $^3S_1$  with  $J^{PC} = 0^{-+}$  and  $1^{--}$ , respectively; the  $L = 1$  states are  $^1P_1$  and  $^3P_{0,1,2}$  with  $J^{PC} = 1^{+-}$ ,  $0^{++}$ ,  $1^{++}$ , and  $2^{++}$ ; the  $L = 2$  states are  $^3D_{1,2,3}$  with  $J^{PC} = 2^{-+}$ ,  $1^{--}$ ,  $2^{--}$ , and  $3^{--}$ , etc.

In addition to the spin-independent potential, there are spin-dependent interactions that produce corrections of order  $(v/c)^2$ . These are found by assuming a specific Lorentz structure for the quark-antiquark interactions. Typically the short distance one-gluon-exchange is taken to be a Lorentz vector interaction and the confinement piece is assumed to be a Lorentz scalar. This gives rise to splittings within multiplets. For example, the  $J/\psi(^3S_1) - \eta_c(^1S_0)$  splitting is attributed to a short distance  $\vec{S}_Q \cdot \vec{S}_{\bar{Q}}$  contact interaction arising from the one-gluon-exchange, while the splittings of the  $P$ -wave  $\chi_c(^3P_{J=0,1,2})$  and higher  $L$  states are due to spin-orbit and tensor spin-spin interactions arising from one-gluon-exchange and a relativistic spin-orbit Thomas precession term. The recent measurement of the  $h_c$  mass by CLEO (12) is an important validation of this picture.

An important approach to understanding the charmonium spectrum is lattice QCD (3). There has been considerable recent progress in calculating the masses of excited  $c\bar{c}$  states and radiative transitions (13), although the results are still not at the point that they can make precision predictions for excited states. However, lattice QCD calculations of the static energy between a heavy quark-antiquark pair are in good agreement with phenomenological potentials (3) and lattice calculations of the spin-dependent potentials also support the phenomenological contact, tensor, and spin-orbit potentials (14).

All charmonium states below the  $D\bar{D}$  “open-charm” mass threshold<sup>8</sup> have been observed. The  $D$ -wave  $c\bar{c}$  states lie just above this threshold and, thus far, only the  $1^3D_1$  state, which is identified as the  $\psi''$  (or  $\psi(3770)$ ), has been observed. The remaining  $n = 1$   $D$ -wave charmonium states, the spin triplet  $^3D_2$  and  $^3D_3$  states and the spin singlet  $^1D_2$  state, are all expected to have masses near  $3800 \text{ MeV}/c^2$  and to be narrow (15, 16, 17, 18) so that it should be possible to observe them (19). The  $n = 2$   $P$  states are the next highest multiplet, with masses predicted to lie in the range of  $3800 - 3980 \text{ MeV}/c^2$  and with total widths of 42, 165, 30, and 87  $\text{MeV}/c^2$  for the  $2^3P_2$ ,  $2^3P_1$ ,  $2^3P_0$ , and  $2^1P_1$ , respectively. We also mention the  $1^3F_4$  since it is relatively narrow for a state so massive, with a predicted mass and width of 4021 and  $\sim 8 \text{ MeV}$  respectively. The  $\eta_c''$  ( $3^1S_0$ ) mass and width are predicted to be  $\sim 4050 \text{ MeV}/c^2$  and  $\sim 80 \text{ MeV}/c^2$ .

**2.1.1 TRANSITIONS AND DECAYS** While the mass value is an important first element for the identification of a new state, more information is usually needed to distinguish between different possibilities. One therefore needs other measurements to form a detailed picture of its internal structure. Decay properties are an important aspect of this.

Electromagnetic transitions can potentially give information on the quantum numbers of a parent state when it decays to a final state with established quantum numbers such as the  $J/\psi$  or  $\chi_{cJ}$ ; studies of the angular correlations among the final state decay particles provide additional information. Quark model predictions also provide an important benchmark against which to test a conventional quarkonium interpretation versus an exotic one. The theory of electromagnetic transitions between quarkonium states is straightforward, and potential models provide detailed predictions that can be compared to experimental measurements to test the internal structure of a state. The leading-order amplitudes are those for electric ( $E1$ ) and magnetic ( $M1$ ) dipole transitions, with the  $E1$  amplitude being the most relevant to our discussion. The predictions for the  $^3P_J \leftrightarrow ^3S_1$  transitions are in good agreement with experimental data (4). We can therefore expect that other electromagnetic transitions will also yield useful information, with the possible exceptions for those cases where there are large dynamical cancellations in the matrix elements, for instance those that involve higher radial excitations that have nodes in their wavefunctions. The status of electromagnetic transitions has been reviewed recently (4) and detailed predictions for charmonium states are given in Refs. (15, 16, 17, 18).

Charmonium states can also undergo hadronic transitions from one  $c\bar{c}$  state to another via the emission of light hadrons. Examples of observed transitions include  $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ ,  $\psi(2S) \rightarrow J/\psi \eta$ ,  $\psi(2S) \rightarrow J/\psi \pi^0$ , and  $\psi(2S) \rightarrow h_c \pi^0$ . The theoretical description of hadronic transitions uses a multipole expansion of the gluonic fields (20, 21, 22, 23, 24, 25) which resembles the usual multipole expansion applied to electromagnetic transitions. Detailed predictions for hadronic transitions are given in Refs. (26, 27, 28, 29, 30, 31, 32, 33).

Charmonium states above the  $D\bar{D}$  and/or  $D\bar{D}^*$  mass threshold can decay to

---

<sup>8</sup>The  $D^0$  and  $D^+$  mesons are the spin-singlet  $S$ -wave ( $1^1S_0$ )  $c\bar{u}$  and  $c\bar{d}$  quark state, respectively.

$DD^{\bar{*}}$  final states.<sup>9</sup> These decays are well described by the  $^3P_0$  model in which a light  $q\bar{q}$  pair is created out of the vacuum with the quantum numbers of the vacuum,  $0^{++}$  (34,35,15,16). The partial decay widths have been calculated for many mesons using this model and the overall qualitative agreement with experiment is very good. Thus, the predictions can provide a useful means of identifying conventional charmonium states. Recent calculations of decay properties of excited charmonium states are given in Refs. (15,16,17,18).

A final decay mechanism of charmonium states is via the annihilation of the  $c\bar{c}$  into final states consisting of gluons and light quark pairs, sometimes with a photon (36,37). However, so far at least, these have not proven to be very important for understanding the new states.

## 2.2 Multiquark states

An early quark model prediction was the existence of multiquark states, specifically bound meson-antimeson molecular states (8,9). In the light quark sector the  $f_0(980)$  and  $a_0(980)$  are considered to be strong candidates for  $K\bar{K}$  molecules. However, in general, it is challenging to definitively identify a light multiquark state in an environment of many broad and often overlapping conventional states. The charmonium spectrum is better defined so that new types of states can potentially be more easily delineated from conventional charmonium states. The observation of the  $X(3872)$ , the first of the  $XYZ$  particles to be seen, brought forward the hope that one can definitively state that a multiquark state has been observed.

Two generic types of multiquark states have been described in the literature. The first, a molecular state, sometimes referred to as a deuson (38), is comprised of two charmed mesons bound together to form a molecule. These states are by nature loosely bound. Molecular states bind through two mechanisms: quark/colour exchange interactions at short distances and pion exchange at large distance (5,38,39) (see Fig. 2) although pion exchange is expected to dominate (5). Molecular states are generally not isospin eigenstates, which gives rise to distinctive decay patterns. Because the mesons inside the molecule are weakly bound, they tend to decay as if they are free. Details are reviewed by Swanson in Ref. (5).

The second type is a tightly bound four-quark state, dubbed a tetraquark, that is predicted to have properties that are distinct from those of a molecular state. In the model of Maiani *et al* (40), the tetraquark is described as a diquark-diantiquark structure in which the quarks group into colour-triplet scalar and vector clusters and the interactions are dominated by a simple spin-spin interaction (see Fig. 2). Here, strong decays are expected to proceed via rearrangement processes followed by dissociation that give rise, for example, to decays such as  $X \rightarrow \rho J/\psi \rightarrow \pi\pi J/\psi$  or  $X \rightarrow DD^* \rightarrow DD\gamma$ .

A prediction that distinguishes multiquark states containing a  $c\bar{c}$  pair from conventional charmonia is the possible existence of multiplets that include members with non-zero charge (e.g.  $[cu\bar{c}\bar{d}]$ ), strangeness (e.g.  $[cd\bar{c}\bar{s}]$ ), or both (e.g.

<sup>9</sup>The  $D^*$  mesons are the spin-triplet  $1^3S_1$  partners of the  $D$  mesons.

$[cu\bar{c}\bar{s}]$  (41).

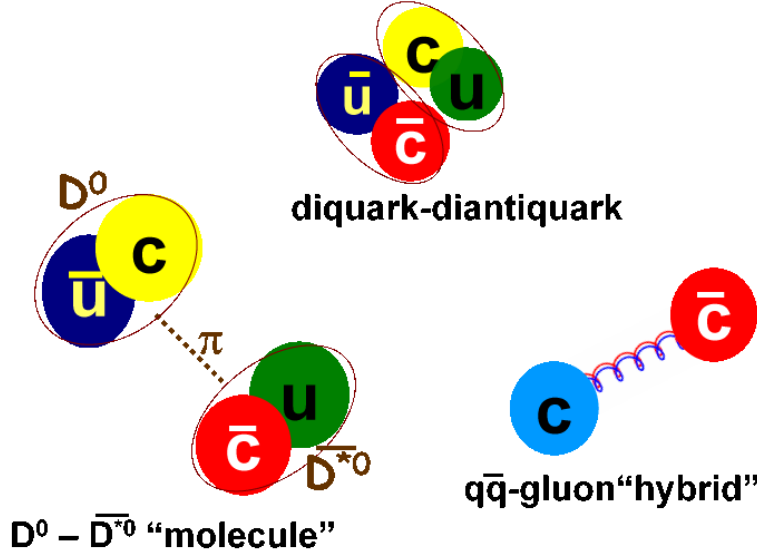


Figure 2: Cartoon representations of molecular states, diquark-diantiquark tetraquark mesons and quark-antiquark-gluon hybrids.

### 2.3 Charmonium hybrids

Hybrid mesons are states with an excited gluonic degree of freedom (see Fig. 2). These are described by many different models and calculational schemes (42). A compelling description, supported by lattice QCD (43,44), views the quarks as moving in adiabatic potentials produced by gluons in analogy to the atomic nuclei in molecules moving in the adiabatic potentials produced by electrons. The lowest adiabatic surface leads to the conventional quarkonium spectrum while the excited adiabatic surfaces are found by putting the quarks into more complicated colour configurations. In the flux-tube model (45), the lowest excited adiabatic surface corresponds to transverse excitations of the flux tube and leads to a doubly degenerate octet of the lowest mass hybrids with quantum numbers  $J^{PC} = 0^{+-}, 0^{-+}, 1^{+-}, 1^{-+}, 2^{+-}, 2^{-+}, 1^{++}$  and  $1^{--}$ . The  $0^{+-}, 1^{-+}, 2^{+-}$  quantum numbers are not possible for a  $c\bar{c}$  bound state in the quark model and are referred to as *exotic* quantum numbers. If observed, they would unambiguously signal the existence of an unconventional state. Lattice QCD and most models predict the lowest charmonium hybrid state to be roughly  $4200 \text{ MeV}/c^2$  in mass (45,42,46).

Charmonium hybrids can decay via electromagnetic transitions, hadronic transitions such as  $\psi_g \rightarrow J/\psi + \pi\pi$ , and to open-charm final states such as  $\psi_g \rightarrow D^{(*)} \bar{D}^{(*)}$ <sup>10</sup>. The partial widths have been calculated using many different models. There are some general properties that seem to be supported by most models and by recent lattice QCD calculations. Nevertheless, since there are

<sup>10</sup>  $D^{**}$  denotes mesons that are formed from  $P$ -wave  $c\bar{q}$  ( $q = u$  or  $d$ ) pairs:  $D_0^*(^3P_0)$ ,  $D_2^*(^3P_2)$  and the  $D_1$  and  $D_1'$  are  $^3P_1 - ^1P_1$  mixtures.

no experimental results against which to test these calculations, one should take their predictions with a grain of salt. Two important decay modes are:

1.  $\psi_g \rightarrow D^{(*,**)} \bar{D}^{(**,*)}$ . Most calculations predict that the  $\psi_g$  should decay to a  $P$ -wave plus an  $S$ -wave meson. In this case  $D(L=0) + D^{**}(L=1)$  final states should dominate over decays to  $D\bar{D}$  and the partial width to  $D\bar{D}^*$  should be very small.
2.  $\psi_g \rightarrow (c\bar{c})(gg) \rightarrow (c\bar{c}) + (\pi\pi, \eta \dots)$  These modes offer clean experimental signatures. If the total width is small, they could have significant branching fractions. One recent lattice QCD calculation finds that these types of decays are potentially quite large,  $\mathcal{O}(10 \text{ MeV}/c^2)$  (47).

## 2.4 Threshold effects

In addition to various types of resonances, thresholds can also give rise to structures in cross sections and kinematic distributions. Possible thresholds include the  $DD^*$ ,  $D^*D^*$ ,  $DD_1$ ,  $D^*D_1$  at  $E_{cm} \sim 38721, 4020, 4287$ , and  $4430 \text{ MeV}$  respectively. At threshold, the cross section is typically dominated by  $S$ -wave ( $L=0$ ) scattering although in some cases higher waves can be important. States in a relative  $S$ -wave with little relative momentum and who live long on the time scale of strong interactions will have enough time to exchange pions and interact (48). Binding is then possible via an attractive  $\pi$  exchange which could occur via couplings such as  $D \leftrightarrow D^*\pi^0$  and can lead to the molecular states discussed above. However, other strong interaction effects might also lead to a repulsive interaction that could result in a virtual state above threshold. Thus, passing through a kinematical threshold can lead to structure in the cross section that may or may not indicate a resonance. In addition, if there are nearby  $c\bar{c}$  states, they will interact with the threshold resulting in mass shifts of both the  $c\bar{c}$  resonance and the threshold-related enhancement. The effects of this channel coupling can be quite significant in the observed cross section, particularly close to thresholds (48,49). This was studied for  $e^+e^-$  annihilation some time ago (50,51,52). Given the observation of new charmonium-like states in channels other than  $J^{PC} = 1^{--}$ , it would be useful to revisit these studies.

## 3 Experimental Background

The observations described below were made possible by the extraordinary performance of the PEP-II  $B$ -factory at the Stanford Linear Accelerator Center (SLAC) in the U.S., and the KEKB  $B$ -factory at the High Energy Accelerator Research Organization (KEK) in Japan. These  $B$ -factories, which were constructed to test the Standard Model mechanism for matter-antimatter asymmetries — so-called  $CP$  violation, are very high luminosity<sup>11</sup> electron ( $e^-$ ) positron ( $e^+$ ) colliders operating at a center-of-mass (cm) energy near  $10,580 \text{ MeV}$ . Electron-positron annihilations at this cm energy produce large numbers of  $B$ -meson anti- $B$ -meson

---

<sup>11</sup>Luminosity is a measure of the beam-beam interaction intensity.



( $B\bar{B}$ ) pairs in a coherent quantum state.<sup>12</sup> Measurements by the BaBar experiment (53) at PEP-II and the Belle experiment (54) at KEKB of the decay patterns of neutral  $B^0\bar{B}^0$  pairs have provided sensitive tests of the Standard Model mechanism for  $CP$  violation.

An unexpected bonus from the  $B$  factories has been a number of interesting contributions to the field of hadron spectroscopy, in particular in the area of charmonium spectroscopy. At  $B$  factories, charmonium mesons are produced in a number of ways. Here we briefly describe the charmonium production mechanisms relevant to the  $XYZ$  states.

**$B$  decays to final states containing  $c\bar{c}$  mesons.**  $B$  mesons decay radioactively with a lifetime of approximately 1.5 picoseconds. At the quark level, the dominant decay mechanism is the weak-interaction transition of a  $b$  quark to a  $c$  quark accompanied by the emission of a virtual  $W^-$  boson, the mediator of the weak interaction. Approximately half of the time, the  $W^-$  boson materializes as a  $s\bar{c}$  pair. As a result, almost half of all  $B$  meson decays result in a final state that contains a  $c$  and  $\bar{c}$  quark. When these final-state  $c$  and  $\bar{c}$  quarks are produced close to each other in phase space, they can coalesce to form a  $c\bar{c}$  charmonium meson.

The simplest charmonium-producing  $B$ -meson decays are those where the  $s$  quark from the  $W^-$  combines with the parent  $B$  meson's  $\bar{u}$  or  $\bar{d}$  quark to form a  $K$  meson. In such decays, to the extent that the  $\bar{u}$  or  $\bar{d}$  quark act as a passive spectator to the decay process, the possible  $J^{PC}$  quantum numbers of the produced  $c\bar{c}$  charmonium system are  $0^{-+}$ ,  $1^{--}$  and  $1^{++}$ . Experimentally it is observed that decays of the type  $B \rightarrow K(c\bar{c})$ , where the  $c\bar{c}$  pair forms a charmonium state with these  $J^{PC}$  values, occur with branching fractions that are all within about a factor of two of  $1 \times 10^{-3}$ . Since both of the  $B$  factory experiments detect more than a million  $B$  mesons a day, the number of detected charmonium states produced via the  $B \rightarrow K(c\bar{c})$  process is substantial. In 2002, the Belle group discovered the  $\eta'_c$ , the first radial excitation of the  $\eta_c$  meson, via the process  $B \rightarrow K\eta'_c$ , where  $\eta'_c \rightarrow K_S K^- \pi^+$  (55).

**Production of  $1^{--}$  charmonium states via initial state radiation.**<sup>13</sup> In  $e^+e^-$  collisions at a cm energy of 10,580 MeV, the initial-state  $e^+$  or  $e^-$  occasionally radiates a high-energy  $\gamma$ -ray, and the  $e^+$  and  $e^-$  subsequently annihilate at a correspondingly reduced cm energy. When the cm energy of the radiated gamma ray ( $\gamma_{ISR}$ ) is between 4000 and 5000 MeV, the  $e^+e^-$  annihilation occurs at cm energies that correspond to the range of  $mc^2$  values of charmonium mesons. Thus, the initial state radiation (ISR) process can directly produce charmonium states with  $J^{PC} = 1^{--}$ . Although this is a suppressed higher-order QED process, the very high luminosities available at the  $B$  factories have made ISR a valuable research tool. For example, the BaBar group used the ISR technique to make measurements of  $J/\psi$  meson decay processes (56).

<sup>12</sup>A  $B$  meson is formed from a  $b$  quark and a  $\bar{d}$  or  $\bar{u}$  quark in a  $1^1S_0$  state.

<sup>13</sup>ISR: initial state radiation

**Charmonium associated production with  $J/\psi$  mesons in  $e^+e^-$  annihilation.** In studies of  $e^+e^-$  annihilations at cm energies near 10,580 MeV, the Belle group made the unexpected discovery that when a  $J/\psi$  meson is produced in the inclusive annihilation process  $e^+e^- \rightarrow J/\psi + \text{anything}$ , there is a high probability that the accompanying system will contain another  $c\bar{c}$  meson system (57). Belle finds, for example, cross sections for the annihilation processes  $e^+e^- \rightarrow J/\psi\eta_c$ ,  $J/\psi\chi_{c0}$  and  $J/\psi\eta'_c$  that are more than an order-of-magnitude larger than were previously expected (58). Thus, the study of systems recoiling against the  $J/\psi$  in inclusive  $e^+e^- \rightarrow J/\psi X$  annihilations is another source of  $c\bar{c}$  states at a  $B$  factory. The very low cross sections for these processes is compensated by the very high luminosities enjoyed by the BaBar and Belle experiments. The conservation of charge-conjugation parity in electromagnetic processes guarantees that the  $C$  quantum number of the accompanying  $c\bar{c}$  system will be  $C = +$ . Experimentally, only the  $0^{-+}$   $\eta_c$  and  $\eta'_c$ , and the  $0^{++}$   $\chi_{c0}$  are observed to be produced in association with a  $J/\psi$ . The  $1^{++}$   $\chi_{c1}$  and  $2^{++}$   $\chi_{c2}$  are not seen. This indicates that this process favors the production of  $J = 0$  states over those with  $J = 1$  and higher.

**Two-photon collisions** In high energy  $e^+e^-$  machines, photon-photon collisions are produced when both an incoming  $e^+$  and  $e^-$  radiate photons that subsequently interact with each other. Two-photon interactions can directly produce particles with  $J^{PC} = 0^{-+}, 0^{++}, 2^{-+}$  and  $2^{++}$ . An example is the CLEO group's confirmation of the existence of the  $\eta'_c$  charmonium state from studies of two-photon production of  $K_S K^\pm \pi^\mp$  final states (59).

## 4 Experimental evidence and theoretical interpretations for the $XYZ$ mesons

In this section we describe experimental characteristics of the  $XYZ$  mesons, discuss their various theoretical interpretations, and present measurements that can distinguish between possibilities and verify their nature.

### 4.1 $X(3872)$

The  $X(3872)$  was first seen in 2003 by Belle as a narrow peak near  $mc^2 = 3872$  MeV in the  $\pi^+\pi^-J/\psi$  invariant mass distribution in  $B^- \rightarrow K^-\pi^+\pi^-J/\psi$  decays (60). Shortly after the Belle announcement, it was observed by the CDF (61) and D0 (62) groups to be produced in high energy proton-antiproton ( $p\bar{p}$ ) collisions at the Fermilab Tevatron, and its production in  $B$  meson decays was subsequently confirmed by BaBar (63). The current world average mass is  $(3871.4 \pm 0.6)$  MeV/ $c^2$ , and its total width is less than 2.3 MeV/ $c^2$  (64).

Both BaBar (65) and Belle (66) have reported evidence for the decay  $X(3872) \rightarrow \gamma J/\psi$ , which indicates that the  $X(3872)$  has  $C = +$ . This implies that the dipion in the  $\pi^+\pi^-J/\psi$  mode has  $C = -$ , suggesting it originates from a  $\rho$ . In fact, analyses of  $X(3872) \rightarrow \pi^+\pi^-J/\psi$  decays by the CDF group have demonstrated that the dipion invariant mass distribution is most simply understood by the hypothesis that it originates from the decay  $\rho \rightarrow \pi^+\pi^-$  (67). The decay of a

charmonium state to  $\rho J/\psi$  would violate isospin, and the evidence for this process provides a strong argument against a charmonium explanation for this state. Evidence for the decay  $X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi$  at a rate comparable to that of  $\pi^+\pi^- J/\psi$  was reported by Belle (66) leading to speculation that the decay proceeds through a virtual  $\omega$ , as had been predicted by Swanson (68). If confirmed, the co-existence of both the  $X(3872) \rightarrow \pi^+\pi^- J/\psi$  and  $X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi$  transitions implies that the  $X(3872)$  is a mixture of both  $I = 0$  and  $I = 1$ , as suggested by Close and Page (69). Angular correlations among the final state particles from  $X(3872) \rightarrow \pi^+\pi^- J/\psi$  decays rule out all  $J^{PC}$  assignments for the  $X(3872)$  other than  $J^{PC} = 1^{++}$  and  $2^{-+}$  (70). Neither of the available charmonium assignments with these  $J^{PC}$  values: the  $1^{++}$   $\chi'_{c1}$  (the  $2^3P_1$   $c\bar{c}$  state) or the  $2^{-+}$   $\eta_{c2}$  (the  $1^1D_1$   $c\bar{c}$  state), are expected to have large branching fractions for the isospin-violating  $\rho J/\psi$  decay channel. Furthermore, a  $2^{-+}$  assignment would require that the decay  $X(3872) \rightarrow \gamma J/\psi$  be a highly suppressed higher multipole, and therefore unlikely. Finally, in the discussion below we identify the  $Z(3930)$  as the  $2^3P_2$  state, thereby setting the  $2^3P_2$  mass at  $\sim 3930$  MeV/ $c^2$ ; this is inconsistent with the  $2^3P_1$  interpretation of the  $X(3872)$ , since the  $2^3P_2 - 2^3P_1$  mass splittings are expected to be lower than  $\sim 50$  MeV/ $c^2$  (18, 15).

An intriguing feature of the  $X(3872)$  is that its measured mass value is very nearly equal to the sum of the masses of the  $D^0$  and  $D^{*0}$  mesons, which has recently been precisely measured by the CLEO experiment to be  $m_{D^0} + m_{D^{*0}} = (3871.81 \pm 0.36)$  MeV/ $c^2$  (71). This close correspondence has led to considerable speculation that the  $X(3872)$  is a molecule-like bound state of a  $D^0$  and a  $\bar{D}^{*0}$  meson (8, 9, 38, 68, 69, 72).<sup>14</sup> The recent measurement of the  $D^0$  mass implies a  $D^{*0}\bar{D}^0$  binding energy of  $(0.6 \pm 0.6)$  MeV/ $c^2$ .

A  $1^{++}$  quantum number assignment for the  $X(3872)$  implies that  $S$ -wave couplings of the  $X$  to  $D^{*0}\bar{D}^0$  is permitted and these result in a strong coupling between the  $X$  and the two mesons. This strong coupling can produce a bound state with a molecular structure just below the two-particle threshold. In this molecular scenario, the decays of the  $X(3872)$  into  $D^{*0}\bar{D}^0\pi^0$  and  $D^*\bar{D}^0\gamma$  proceed through the decays of its constituent  $D^{*0}$  with branching ratios similar to those of the  $D^{*0}$  (72, 69). The  $D^0\bar{D}^{*0}$  molecule wavefunction is expected to contain some admixture of  $\rho J/\psi$  and  $\omega J/\psi$ . This explains the isospin-violating  $\rho J/\psi$  decay mode and also successfully predicted the  $\pi^+\pi^-\pi^- J/\psi$  decay width (68). A further prediction of the molecule explanation is the existence of a molecular  $D^*\bar{D}^*$  state with mass 4019 MeV/ $c^2$  and  $J^{PC} = 0^{++}$  decaying to  $\omega J/\psi$ ,  $\eta\eta_c$  and  $\eta'\eta_c$  (5). A related possibility is that the  $X(3872)$  is dynamically generated (73).

Maiani *et al* advocate a tetraquark explanation for the  $X(3872)$  (40, 74). A prediction of the tetraquark interpretation is the existence of a second neutral  $X$  state that is strongly produced in neutral  $B^0$  mesons decays to  $K^0\pi^+\pi^- J/\psi$  with a mass that differs by  $8 \pm 3$  MeV/ $c^2$  from the mass of the  $X(3872)$  produced in  $B^+$  decays. They also predicted the existence of charged isospin partner states.

Belle recently reported a  $\sim 7\sigma$  signal for  $X(3872)$  production in neutral  $B$  me-

<sup>14</sup>In this review the inclusion of charge conjugate states is always implied. *E.g.*, “a  $D^0$  and a  $\bar{D}^{*0}$  meson” could also mean a  $D^{*0}$  and a  $\bar{D}^0$  meson.

son decays (*i.e.*,  $B^0 \rightarrow K_S^0 X(3872)$ ), which is shown, together with the signal from charged  $B$  meson decays, in Fig. 3. They determine a mass difference between the  $X(3872)$  produced in charged versus neutral  $B$  decays of  $0.9 \pm 0.9 \text{ MeV}/c^2$  (75), which is consistent with zero, and inconsistent with the tetraquark-model prediction. This confirms an early lower-precision result from BaBar (76).

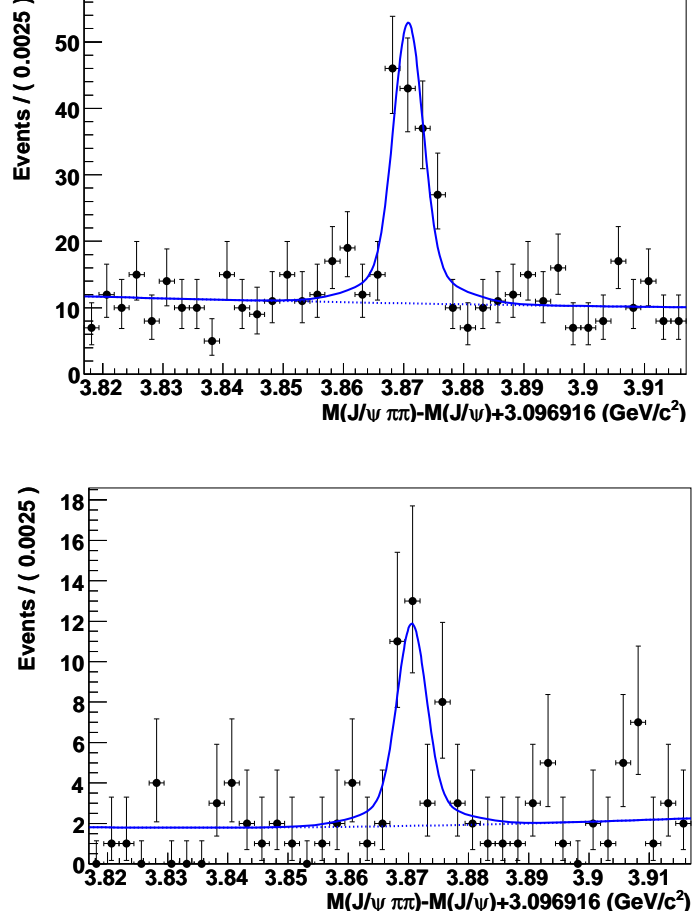


Figure 3: The  $M(\pi^+\pi^-J/\psi)$  mass distributions produced in charge  $B^-$  (top) and neutral  $B^0$  (bottom) decays to  $K\pi^+\pi^-J/\psi$  final states (75).

The BaBar group also searched for a charged partner of the  $X(3872)$  in the  $\rho^- J/\psi$  decay channel. They found no signal and excluded an isovector hypothesis for the  $X(3872)$  with high confidence (77).

In studies of the decay process  $B \rightarrow K D^0 \bar{D}^0 \pi^0$ , both Belle (78) and BaBar (79) report narrow enhancements just above the  $m_{\pi^0} + 2m_{D^0}$  mass threshold. The peak mass values for the two observations ( $3875.2 \pm 1.9 \text{ MeV}/c^2$  for Belle and  $(3875.1 \pm 1.2) \text{ MeV}/c^2$  for BaBar) are in good agreement with each other and about four standard deviations higher than the  $X(3872)$  mass measured with  $\pi^+\pi^-J/\psi$  decays, which may be evidence for the second  $X$  state predicted in Ref. (40). BaBar observes this enhancement in both the  $D^0 \bar{D}^0 \pi^0$  and  $D^0 \bar{D}^0 \gamma$  modes, which strongly supports the presence of the  $D^0 \bar{D}^{*0}$  intermediate state in

the decay of this (possibly) new  $X$ .

Dunwoodie and Ziegler argue that the mass shift between the two sets of observations is a result of the sensitivity of the peak position of the  $D^*\bar{D}^0$  invariant mass distribution to the final state orbital momentum because of the proximity of the  $X(3872)$  to the  $D^*\bar{D}^0$  threshold (80). Another explanation put forward in Refs. (81), (82) and (83) is that the line shapes of the  $X(3872)$  depend on its decay channel and are different for the  $J/\psi\pi^+\pi^-$ ,  $J/\psi\pi^+\pi^-\pi^0$ , and  $D^0\bar{D}^0\pi^0$  channels. In both explanations the more massive enhancement is not regarded as a separate state, but a manifestation of the  $X(3872)$ .

To summarize, there is an emerging consensus that the  $X(3872)$  is a multiquark state with the molecular interpretation being favoured due to its proximity to the  $DD^*$  threshold.

## 4.2 $XYZ$ particles with $mc^2$ near 3940 MeV

Three, apparently distinct,  $XYZ$  candidate states have been observed with masses near 3940 MeV/ $c^2$ . These include the  $X(3940)$ , seen as a peak in the  $DD\bar{D}^*$  invariant mass in the process  $e^+e^- \rightarrow J/\psi DD\bar{D}^*$  (84); the  $Y(3940)$ , a peak in the  $\omega J/\psi$  mass spectrum seen in  $B \rightarrow K\omega J/\psi$  decays (85); and the  $Z(3930)$ , a peak in the invariant mass distribution of  $DD\bar{D}$  meson pairs produced in two-photon collisions (86).

**4.2.1 THE  $Z(3930)$**  The  $Z(3930)$  seems easiest to understand. It is a peak reported by Belle in the spectrum of  $DD\bar{D}$  mesons produced in  $\gamma\gamma$  collisions, with mass and width  $M = 3929 \pm 6$  MeV/ $c^2$  and  $\Gamma = 29 \pm 10$  MeV/ $c^2$  (86). The  $DD\bar{D}$  decay mode makes it impossible for the  $Z(3930)$  to be the  $\eta_c(3S)$  state. The two-photon production process can only produce  $DD\bar{D}$  in a  $0^{++}$  or  $2^{++}$  state and for these, the  $dN/d\cos\theta^*$  distribution, where  $\theta^*$  is the angle between the  $D$  meson and the incoming photon in the  $\gamma\gamma$  cm, are quite distinct: flat for  $0^{++}$  and  $\propto \sin^4\theta^*$  for  $2^{++}$ . The Belle measurement strongly favors the  $2^{++}$  hypothesis (see Fig. 4), making the  $Z(3930)$  a prime candidate for the  $\chi'_{c2}$ , the  $2^3P_2$  charmonium state. The predicted mass of the  $\chi_{c2}(2P)$  is 3972 MeV/ $c^2$  and the predicted total width assuming the observed mass value is  $\Gamma_{\text{total}}(\chi_{c2}(2P)) = 28.6$  MeV/ $c^2$  (87, 15,18), in good agreement with the experimental measurement. Furthermore, the two-photon production rate for the  $Z(3930)$  is also consistent with expectations for the  $\chi'_{c2}$  (88). The  $\chi_{c2}(2P)$  interpretation could be confirmed by observation of the  $DD\bar{D}^*$  final state, which is expected to have a  $\mathcal{B} \sim 25\%$  (18,15), and the radiative transition  $\chi_{c2}(2P) \rightarrow \gamma\psi(2S)$  which is predicted to have a partial width of  $\mathcal{O}(100\text{keV})$  (18,15).

**4.2.2 THE  $X(3940)$  (AND  $X(4160)$ )** Belle observed the  $X(3940)$  in double-charmonium production in the reaction  $e^+e^- \rightarrow J/\psi + X$  with mass  $M = 3943 \pm 8$  MeV/ $c^2$  and intrinsic width  $\Gamma < 52$  MeV/ $c^2$  at the 90% C.L. (84). In addition to the  $X(3940)$ , Belle observed the well known charmonium states  $\eta_c$ ,  $\chi_{c0}$ , and  $\eta_c(2S)$  with properties consistent with those from other determinations. While a distinct signal for  $X(3940) \rightarrow DD\bar{D}^*$  is seen, there is no evidence for the  $X(3940)$  in either the  $DD\bar{D}$  or  $\omega J/\psi$  decay channels. If the  $X(3940)$  has  $J = 0$ , as seems to be the case for mesons produced via this production mechanism, the absence of a

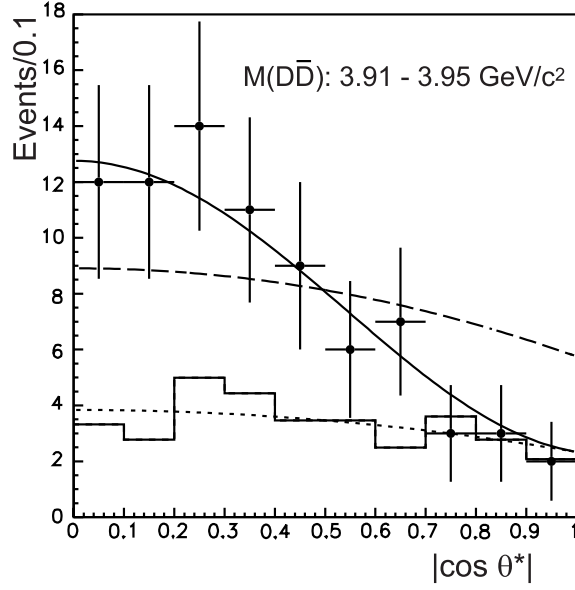


Figure 4: Belle’s  $\chi_{c2}(2P)$  candidate (86):  $\cos \theta^*$ , the angle of the  $D$  meson relative to the beam axis in the  $\gamma\gamma$  center-of-mass frame for events with  $3.91 < m(D\bar{D}) < 3.95$  GeV; the data (circles) are compared with predictions for  $J = 2$  (solid) and  $J = 0$  (dashed). The background level can be judged from the solid histogram or the interpolated smooth dotted curve.

substantial  $D\bar{D}$  decay mode strongly favors  $J^P = 0^{-+}$ , for which the most likely charmonium assignment is the  $\eta_c''$ , the  $3^1S_1$  charmonium state. The fact that the lower mass  $\eta_c(1S)$  and  $\eta_c(2S)$  are also produced in double charm production seems to support this assignment. The predicted width for a  $3^1S_0$  state with a mass of  $3943$  MeV/ $c^2$  is  $\sim 50$  MeV/ $c^2$  (18), which is in acceptable agreement with the measured  $X(3940)$  width.

However, there are problems with this assignment, the first being that the measured mass of the  $X(3940)$ , recently updated by Belle to be  $(3942 \pm 8)$  MeV/ $c^2$  (89), is below potential model estimates of  $\sim 4050$  MeV/ $c^2$  or higher (90). A further complication is the recent observation by Belle of a mass peak in the  $D^*\bar{D}^*$  system recoiling from a  $J/\psi$  in the process  $e^+e^- \rightarrow J/\psi D^*\bar{D}^*$  (89). This state, designated as  $X(4160)$ , has a mass of  $(4156 \pm 29)$  MeV/ $c^2$  and a total width of  $\Gamma = (139^{+113}_{-65})$  MeV/ $c^2$ . Using similar arguments, this latter state could also be attributed to the  $3^1S_0$  state. But the  $X(4160)$  mass is well above expectations for the  $3^1S_0$  and well below those for the  $4^1S_0$ , which is predicted to be near  $4400$  MeV/ $c^2$  (90). Although *either* the  $X(3940)$  *or* the  $X(4160)$  might conceivably fit a charmonium assignment, it seems very unlikely that both of them could be accommodated as  $c\bar{c}$  states. The  $\eta_c''$  assignment can be tested by studying the angular distribution of the  $D\bar{D}^*$  final state and to observe it in  $\gamma\gamma \rightarrow D\bar{D}^*$ .

**4.2.3 THE  $Y(3940)$**  Belle’s observation of the  $Y(3940) \rightarrow \omega J/\psi$  in  $B \rightarrow K\omega J/\psi$  decays (85) has recently been confirmed by BaBar (91). Belle reports a mass and width of  $M = (3943 \pm 17)$  MeV/ $c^2$  and  $\Gamma = (87 \pm 34)$  MeV/ $c^2$

while BaBar reports the preliminary values of  $M = (3914.3^{+4.1}_{-3.8}) \text{ MeV}/c^2$  and  $\Gamma = (33^{+12}_{-8}) \text{ MeV}/c^2$ , which are both somewhat smaller than Belle's values. The measured product branching fractions agree:  $\mathcal{B}(B \rightarrow KY(3940))\mathcal{B}(X(3940) \rightarrow \omega J/\psi) = (7.1 \pm 3.4) \times 10^{-5}$  (Belle), and  $\mathcal{B}(B \rightarrow KY(3940))\mathcal{B}(X(3940) \rightarrow \omega J/\psi) = (4.9 \pm 1.1) \times 10^{-5}$  (BaBar). These values, together with an assumption that the branching fraction  $\mathcal{B}(B \rightarrow KY(3940))$  is less than or equal to  $1 \times 10^{-3}$ , a value that is typical for allowed  $B \rightarrow K + \text{charmonium}$  decays, imply a partial width  $\Gamma(Y(3940) \rightarrow \omega J/\psi) > 1 \text{ MeV}/c^2$ , which is at least an order-of-magnitude higher than those for hadronic transitions between any of the established charmonium states. The Belle group's 90% confidence level limit on  $\mathcal{B}(X(3940) \rightarrow \omega J/\psi) < 26\%$  (84) is not stringent enough to rule out the possibility that the  $X(3940)$  and the  $Y(3940)$  are the same state.

The mass and width of  $Y(3940)$  suggest a radially excited  $P$ -wave charmonium state. We expect that  $\chi_{c1}(2P) \rightarrow D\bar{D}^*$  would be the dominant decay mode, with a predicted partial width of  $140 \text{ MeV}/c^2$  (92), which is consistent with the width of the  $Y(3940)$  within the theoretical and experimental uncertainties. Furthermore, the  $\chi_{c1}$  is also seen in  $B$ -decays. However, the large branching fraction for  $Y \rightarrow \omega J/\psi$  is unusual for a  $c\bar{c}$  state above open charm threshold. A possible explanation for this unusual decay mode is that rescattering through  $D\bar{D}^*$  is responsible:  $1^{++} \rightarrow D\bar{D}^* \rightarrow \omega J/\psi$ . Another contributing factor might be mixing with the molecular state that is tentatively identified with the  $X(3872)$ . The  $\chi_{c1}(2P)$  assignment can be tested by searching for the  $D\bar{D}$  and  $D\bar{D}^*$  final states and by studying their angular distributions. With the present experimental data, a  $\chi_{c0}(2P)$  assignment cannot be ruled out.

### 4.3 The $J^{PC} = 1^{--}$ states produced via ISR

Using the ISR process, BaBar discovered unexpected peaks near  $4300 \text{ MeV}/c^2$  in the  $\pi^+\pi^-J/\psi$  and  $\pi^+\pi^-\psi'$  channels. The partial widths for these decay channels are much larger than usual for charmonium states. Since these states are produced via the ISR process, they have  $J^{PC} = 1^{--}$ . All of the  $1^{--}$  charmonium levels in the  $4000\text{--}4500 \text{ MeV}/c^2$  mass range have already been assigned to the well established  $\psi(4040)$ ,  $\psi(4160)$  and  $\psi(4415)$  mesons, which match well their assignments to the  $3^3S_1$ ,  $2^3D_1$  and  $4^3S_1$   $c\bar{c}$  states, respectively. The quark model predicts additional charmonium  $1^{--}$  states, but at higher masses;  $3^3D_1(4520)$ ,  $5^3S_1(4760)$ ,  $4^3D_1(4810)$ , etc. (93). The experimental situation is likely complicated and obscured by interference between these resonances which can affect the parameters extracted from the measurements.

**4.3.1 THE  $Y(4260)$   $\pi^+\pi^-J/\psi$  RESONANCE** The BaBar group measured the energy dependence of the cross section for  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  using ISR radiation events at a primary cm energy of  $10,580 \text{ MeV}$ . They found a broad enhancement around  $4260 \text{ MeV}$  (94) that they dubbed the  $Y(4260)$ . A fit to the peak with a single Breit Wigner resonance shape yields a mass  $M = (4259 \pm 10) \text{ MeV}/c^2$  and full width  $\Gamma = (88 \pm 24) \text{ MeV}/c^2$ , values that are quite distinct from those of other established charmonium states. Although it is well above the threshold for decaying into  $D\bar{D}$ ,  $D\bar{D}^*$  or  $D^*\bar{D}^*$  meson pairs, there is no evidence for the

$Y(4260)$  in any of these channels (95). In fact, there appears to be a dip in the measured  $e^+e^-$  total annihilation cross section at this energy (96). An analysis using total cross section data for  $e^+e^-$  annihilation into hadrons at cm energies around 4260 MeV results in a 90% CL lower limit on the partial decay width  $\Gamma(Y(4260) \rightarrow \pi^+\pi^-J/\psi) > 1.6 \text{ MeV}/c^2$  (97), which is much larger than the partial widths for equivalent transitions among established  $1^{--}$  charmonium states. The  $Y(4260)$  peak was confirmed by both CLEO (98) and Belle (99). Belle reported a second, broader  $\pi^+\pi^-J/\psi$  peak near 4008 MeV/ $c^2$ . It is currently not known whether this latter enhancement is due to the  $\psi(4040)$ , a dynamical threshold enhancement, or another meson state.

**4.3.2 THE  $\pi^+\pi^-\psi'$  RESONANCES AT 4370 MEV/ $c^2$  AND 4660 MEV/ $c^2$**  BaBar also found a broad peak in the cross section for  $e^+e^- \rightarrow \pi^+\pi^-\psi'$  that is distinct from the  $Y(4260)$ ; its peak position and width are not consistent with those of the  $Y(4260)$  (100). The BaBar observation was subsequently confirmed by a Belle study that used a larger data sample (101). Belle found that the  $\pi^+\pi^-\psi'$  mass enhancement is, in fact, produced by two distinct peaks, one, the  $Y(4360)$  with  $M = (4361 \pm 13) \text{ MeV}/c^2$  and  $\Gamma = (74 \pm 18) \text{ MeV}/c^2$  and a second, the  $Y(4660)$  with  $M = (4664 \pm 12) \text{ MeV}/c^2$  and  $\Gamma = (48 \pm 15) \text{ MeV}/c^2$  (101). These masses and widths are not consistent with any of the established  $1^{--}$  charmonium states, and no sign of a peak at either of these masses is evident either in the  $e^+e^-$  total annihilation cross section (96) or in the exclusive cross sections  $e^+e^- \rightarrow D\bar{D}$ ,  $D\bar{D}^*$ , or  $D^*\bar{D}^*$  (95), which indicates that the  $\pi^+\pi^-\psi'$  partial width for these states is unusually large (at least by charmonium standards). Moreover, as is evident in Fig. 5, which shows the recent Belle results for  $\pi^+\pi^-J/\psi$  (top) and  $\pi^+\pi^-\psi'$  (bottom) with the same horizontal mass scales, there is no sign of either the  $Y(4360)$  or  $Y(4660)$  in the  $\pi^+\pi^-J/\psi$  channel; nor is there any sign of the  $Y(4260)$  peak in the  $\pi^+\pi^-\psi'$  mass spectrum.

**4.3.3 DISCUSSION** The discovery of the  $Y(4260)$ ,  $Y(4360)$ , and  $Y(4660)$  appears to represent an overpopulation of the expected charmonium  $1^{--}$  states. The absence of open charm production is also inconsistent with a conventional  $c\bar{c}$  explanation. While Ding *et al* argue that the  $Y(4360)$  and  $Y(4660)$  are conventional  $c\bar{c}$  states, in particular the  $3^3D_1$  and  $5^3S_1$ , respectively (102), their masses are inconsistent with other quark model calculations (93). Other possible explanations of these state include charmonium hybrids,  $S$ -wave charm meson thresholds, or multiquark states; either  $cq\bar{c}\bar{q}$  tetraquarks or  $DD_1$  and  $D^*D_0$  molecules. Liu suggests that the peak at 4008 MeV/ $c^2$  is related to the  $D^*\bar{D}^*$  threshold and could be a  $D^*\bar{D}^*$  molecule where the  $D^*$  and  $\bar{D}^*$  are in a  $P$ -wave (103).

The  $Y(4260)$  has been around the longest and has received the most scrutiny. The first unaccounted-for  $c\bar{c}$  state is the  $\psi(3^3D_1)$  which is predicted to have a mass of  $M(3^3D_1) \simeq 4500 \text{ MeV}/c^2$ , much too heavy to be the  $Y(4260)$ . Numerous explanations have been proposed: it is a  $D^*(2010)\bar{D}_1(2420)$  threshold enhancement (104), a  $D\bar{D}_1$  or  $D^*\bar{D}_0^0$  bound state (105,106,107), or a  $cs\bar{c}\bar{s}$  tetraquark (108). In the latter cases, the  $Y$  would decay to  $D\pi\bar{D}^*$ , where the  $D$  and  $\pi$  are not from a  $D^*$ . One would expect this mode to have a large width so its non-observation disfavors the tetraquark/molecule explanations.



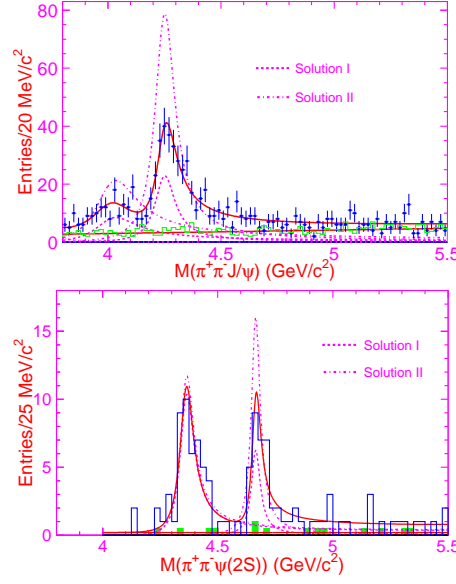


Figure 5: The  $\pi^+\pi^-J/\psi$  (Top) and  $\pi^+\pi^-\psi'$  (Bottom) invariant mass distributions for the ISR processes  $e^+e^- \rightarrow \gamma\pi^+\pi^-J/\psi(\psi')$ , from Refs. (99,101). The curves indicate the results of fits of interfering Breit Wigner resonances to the data.

An attractive interpretation is that the  $Y(4260)$  is a charmonium hybrid (109, 110, 111). The flux tube model predicts the lowest  $c\bar{c}$  hybrid to have a mass that is  $\sim 4200 \text{ MeV}/c^2$  (42), and this is consistent with lattice gauge theory predictions (46). Lattice gauge theory found that the  $b\bar{b}$  hybrids have large couplings to closed flavor channels (47) which is similar to the BaBar observation of  $Y \rightarrow J/\psi\pi^+\pi^-$  and is much larger than is typical for transitions involving conventional charmonium states. A prediction of the hybrid hypothesis is that the dominant hybrid-charmonium open-charm decay modes are expected to be a meson pair with an  $S$ -wave ( $D, D^*, D_s, D_s^*$ ) and a  $P$ -wave ( $D_J, D_{sJ}$ ) in the final state (110). The dominant decay mode is expected to be  $D\bar{D}_1$ . Evidence for a large  $D\bar{D}_1$  signal would be strong evidence for the hybrid interpretation. A complication is that the  $D\bar{D}_1$  threshold is  $4287 \text{ MeV}/c^2$  if we consider the lightest  $D_1$  to be the narrow state at  $2422 \text{ MeV}/c^2$  (64). Note that both the  $Y(4370)$  and the  $Y(4660)$  are well above the  $D\bar{D}_1$  mass threshold. If the same hybrid interpretation is applied to them, decays to  $D\bar{D}_1$  should be very strong and one would expect peaks in the exclusive cross sections for  $e^+e^- \rightarrow D\bar{D}_1$  at these masses.

Lattice gauge theory also suggests that we search for other closed charm modes with  $J^{PC} = 1^{--}$ :  $J/\psi\eta, J/\psi\eta', \chi_{cJ}\omega$  and more. If the  $Y(4260)$  is a hybrid it is expected to be a member of a multiplet consisting of eight states with masses in the  $4000$  to  $4500 \text{ MeV}/c^2$  mass range. It would be most convincing if some of these partners were found, especially those with exotic  $J^{PC}$  quantum numbers. In the flux-tube model the exotic states have  $J^{PC} = 0^{+-}, 1^{-+}$ , and  $2^{+-}$  while the non-exotic low-lying hybrids have  $0^{-+}, 1^{+-}, 2^{-+}, 1^{++}$ , and  $1^{--}$ .

The current situation regarding the  $1^{--}$  states produced via ISR is clearly unsettled. Coupled-channel effects and rescattering of pairs of charmed mesons could play an important role (49) in understanding these peaks. Further complications that need to be understood are couplings to channels near thresholds that can interfere with conventional  $c\bar{c}$  states. The challenge in extracting resonance parameters in this environment is highlighted by the recent BES analysis which attempted to take into account the interference between these broad resonances and found substantial variations in the resonance parameters compared to a fit that didn't take into account interference (112). Clearly, more experimental information on the decay properties of these states and more theoretical work on coupled channel and interference effects are needed if a better understanding of these states is to be achieved.

#### 4.4 The $Z^+(4430) \rightarrow \pi^+\psi'$

In Summer 2007, the Belle group reported on a study of the  $B \rightarrow K\pi^+\psi'$  decay process where they observed a relatively narrow enhancement in the  $\pi^+\psi'$  invariant mass distribution at  $M = (4433 \pm 5) \text{ MeV}/c^2$  (113) (see Fig. 6). A fit with a single relativistic Breit Wigner, indicated by the smooth curve in Fig. 6, yields a total width of  $\Gamma = (45^{+35}_{-18}) \text{ MeV}/c^2$ , which is too narrow to be caused by interference effects in the  $K\pi$  channel. The  $B$  meson decay rate to this state, which is called  $Z^+(4430)$ , is similar to that for decays to the  $X(3872)$  and  $Y(3940)$ , which implies that the  $Z^+(4430)$  has a substantial branching fraction (*i.e.* greater than a few percent) to  $\pi^+\psi'$  and, thus, a partial decay width for this mode that is on the MeV scale. There are no reports of a  $Z^+(4430)$  signal in the  $\pi^+J/\psi$  decay channel.

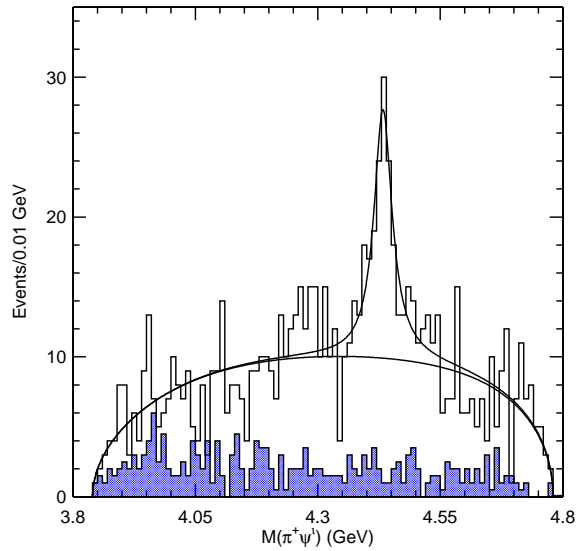


Figure 6: The  $\pi^+\psi'$  invariant mass distribution for  $B \rightarrow K\pi^+\psi'$  decays (113). The shaded histogram is the estimated background. The curve is the result of a fit described in the text.

Among the  $XYZ$  exotic meson candidates, the  $Z^+(4430)$  is unique in that it has a non-zero electric charge, a feature that cannot occur for  $c\bar{c}$  charmonium states or  $c\bar{c}$ -gluon hybrid mesons. It is, therefore, a prime candidate for a multiquark meson.

There have been a number of theoretical explanations. Because it is close to the  $D^*\bar{D}_1(2420)$  threshold, Rosner suggested it is an  $S$ -wave threshold effect (114), while others consider it to be a strong candidate for a  $D^*\bar{D}_1(2420)$  molecule (115, 116, 117). Maiani *et. al.* suggested that the  $Z(4430)$  is a diquark-diantiquark state with flavour  $[cu][\bar{c}\bar{d}]$  and is the radial excitation of a  $X_{u\bar{d}}^+(1^{+-}; 1S)$  state with mass 3880 MeV/c<sup>2</sup> (118). The tetraquark hypothesis implies that the  $Z(4433)^+$  will have neutral partners decaying to  $\psi(2S) + \pi^0/\eta$  or  $\eta_c(2S) + \rho^0/\omega$ . If the  $X^+(4430)$  is a molecule, assuming that the  $D^*\bar{D}_1$  is in a relative  $S$ -wave, it will have  $J^P = 0^-, 1^-,$  or  $2^-$ , with the lightest state expected to be the  $0^-$  (117). In contrast, a tetraquark would have  $J^P = 1^+$ . The molecule will decay via the decay of its constituent mesons into  $D^*D^*\pi$  (115) while the tetraquark will fall apart into  $D\bar{D}^*, D^*\bar{D}^*, J/\psi\pi, J/\psi\rho, \eta_c\rho$  and  $\psi(2S)\pi$ , but not into  $D\bar{D}$  due to its unnatural spin-parity (119). The tetraquark model also predicts a second nearby state with mass  $\sim 4340$  MeV/c<sup>2</sup> also decaying into the  $\psi'\pi^+$  final state (118).

#### 4.5 Are there corresponding states in the $s$ and $b$ quark sectors?

Many of the models proposed to explain the  $XYZ$  states predict analogous states in the  $b\bar{b}$  and  $s\bar{s}$  sectors. In the  $s\bar{s}$  sector the  $f_0(980)$  and  $a_0(980)$  have long been identified as candidates for  $K\bar{K}$  molecules. In the  $b\bar{b}$  sector  $B\bar{B}^*, B^*\bar{B}^*$  molecules (38) in addition to a  $B^*\bar{B}_1$  molecule bound state are expected (120, 116, 119). In addition, threshold effects due to  $\pi$ -exchange and hybrid states are also expected in both the  $b\bar{b}$  and  $s\bar{s}$  sectors (48). It is therefore of great interest to see if there are corresponding exotic meson candidates in the  $b$ -quark and  $s$ -quark sectors. Some recent results indicate that this may be the case.

**4.5.1 AN ANOMALOUS PARTIAL WIDTH FOR “ $\Upsilon(5S)$ ”  $\rightarrow \pi^+\pi^-\Upsilon(1S)$**  The bottomonium states are the  $b\bar{b}$  counterparts of the charmonium mesons. For these, the  $J^{PC} = 1^{--}$  states are the  $\Upsilon(nS)$  mesons. Most of the data accumulated by the KEKB and PEP-II  $B$ -factory experiments is at the cm energy that corresponds to the peak of the  $\Upsilon(4S)$ , the  $4^3S_1$   $b\bar{b}$  state at 10,580 MeV/c<sup>2</sup>, which is just above the threshold for producing  $B\bar{B}$  meson pairs. Using their large  $\Upsilon(4S)$  data sample, the BaBar group measured the partial widths for  $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(2S)$  and  $\pi^+\pi^-\Upsilon(1S)$  of  $(1.8 \pm 0.4)$  keV/c<sup>2</sup> and  $(1.7 \pm 0.5)$  keV/c<sup>2</sup>, respectively (121), the latter value has been confirmed by Belle (122) and both values are similar to those for dipion transitions from the  $\Upsilon(3S)$  to the  $\Upsilon(2S)$  ( $0.6 \pm 0.2$  keV/c<sup>2</sup>) and  $\Upsilon(1S)$  ( $1.2 \pm 0.2$  keV/c<sup>2</sup>) (64).

Recently, Belle accumulated a much smaller data sample at 10,870 MeV, the peak of the  $\Upsilon(5S)$ , and found huge signals for  $\pi^+\pi^-\Upsilon(1S)$ ,  $\pi^+\pi^-\Upsilon(2S)$  and  $\pi^+\pi^-\Upsilon(3S)$  (see Fig. 7). If these are attributed to dipion transitions from the  $\Upsilon(5S)$ , the partial widths are (123):

$$\Gamma(\text{“}\Upsilon(5S)\text{”} \rightarrow \pi^+\pi^-\Upsilon(1S)) = (590 \pm 100) \text{ keV/c}^2 \quad (1)$$

$$\begin{aligned}\Gamma(\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(2S)) &= (850 \pm 175) \text{ keV}/c^2 \\ \Gamma(\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(3S)) &= (520 \pm 220) \text{ keV}/c^2,\end{aligned}$$

which are more than two-orders-of-magnitude larger than those for the corresponding transitions for the  $\Upsilon(4S)$ ,  $\Upsilon(3S)$  or  $\Upsilon(2S)$ . A likely interpretation is that a  $b\bar{b}$  counterpart of the  $Y(4260)$ , the  $Y_b$ , may be overlapping the  $\Upsilon(5S)$ , and this is the source of the anomalous  $\pi^+\pi^-\Upsilon(nS)$  production (124).<sup>15</sup> As noted in Ref. (123), this hypothesis could be verified by measuring the cm-energy dependence of the cross sections for  $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$  around 10,870 MeV. Another suggestion is that the anomalously high  $\pi^+\pi^-$  transitions could be due to the mixing of conventional  $b\bar{b}$  states with thresholds and subsequent rescattering (48). This could be tested by looking for other final states.

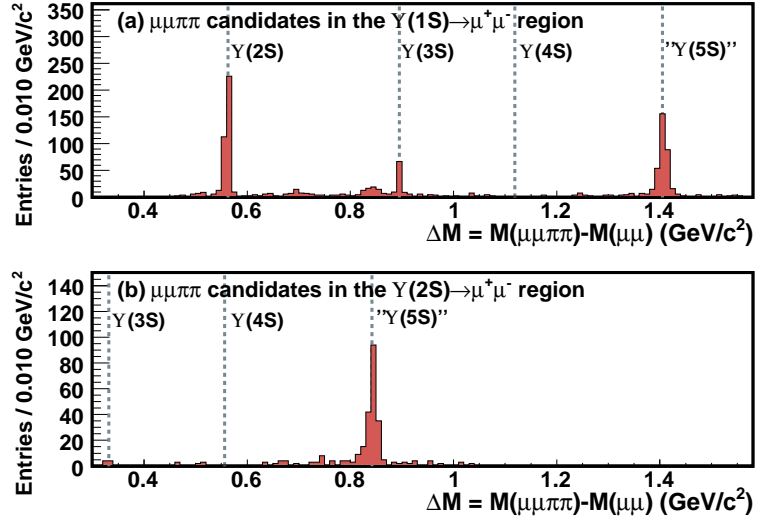


Figure 7: Belle’s  $M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$  mass difference distributions for events with (a)  $M(\mu^+\mu^-) = \Upsilon(1S)$  and (b)  $M(\mu^+\mu^-) = \Upsilon(2S)$  (Ref. (123)). Vertical dashed lines show the expected locations for  $\Upsilon(nS) \rightarrow \pi^+\pi^-\Upsilon(1,2S)$  transitions. (The  $\Upsilon(2,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$  signals in Fig. 7(a) are produced by radiative-return transitions  $e^+e^- \rightarrow \gamma_{ISR}\Upsilon(2,3S)$ .)

4.5.2 THE  $Y(2175) \rightarrow \phi f_0(980)$ ; AN  $s\bar{s}$  COUNTERPART OF THE  $Y(4260)$ ? In a study of the ISR process  $e^+e^- \rightarrow \gamma_{ISR}\phi f_0(980)$ , where  $\phi \rightarrow K^+K^-$  and  $f_0(980) \rightarrow \pi^+\pi^-$ , the BaBar group observed a distinct resonance-like peak in the  $\phi f_0(980)$  invariant mass distribution at a mass  $M = (2175 \pm 18) \text{ MeV}/c^2$  with a full width  $\Gamma = (58 \pm 26) \text{ MeV}/c^2$  (125). Recently, a  $\phi f_0(980)$  invariant mass peak with mass and width values consistent with the BaBar observation was seen in  $J/\psi \rightarrow \phi f_0(980)\eta$  decays by the BES group (126). The  $\phi$  meson is the  $s\bar{s}$  counterpart of the  $J/\psi$ , and the observed structure, called the  $Y(2175)$ , has similar production and decay characteristics as the  $Y(4260)$ . This has led to some speculation that the  $Y(2175)$  may be the  $Y_s$ , *i.e.* an  $s$ -quark system counterpart to the  $Y(4260)$  (127). While this is an intriguing idea, the experimental situation

<sup>15</sup>This is the reason for the quotation marks around  $\Upsilon(5S)$  in Eq. 1.

is far from conclusive, and the  $Y(2175)$  may very well be an excited state of the  $\phi$  or some other  $q\bar{q}$  meson. Ding and Yan (128) have suggested that studying the decay modes of the  $Y(2175)$  can distinguish between the conventional  $2^3D_1(s\bar{s})$  and strangeonium hybrid explanations. Specifically, the dominant decay modes of an  $s\bar{s}$  hybrid are  $K_1(1400)\bar{K}$  and  $K_1(1270)\bar{K}$  with, for example, the decays to  $K\bar{K}$  or  $K^*\bar{K}^*$  forbidden. In contrast the  $2^3D_1(s\bar{s})$  is expected to have large branching fractions to  $K\bar{K}$  and  $K^*\bar{K}^*$ . The  $3^3S_1(s\bar{s})$  is not considered to be a candidate as it is predicted to be quite broad. Further studies of the properties of the  $Y(2175)$ , and searches for  $s$ -quark counterparts of other  $XYZ$  states could help clarify the situation.

#### 4.6 Summary

The  $B$ -factory experiments have uncovered a large (and rapidly growing) number of candidates for charmonium and charmonium-like meson states, many of which cannot be easily accommodated by current theoretical expectations for  $c\bar{c}$  mesons. A number of models have been proposed to explain these states, including meson-antimeson molecules, diquark-diantiquark bound states,  $c\bar{c}$ -gluon hybrids and threshold effects. None of the proposed mechanisms easily accounts for all of the observations. Moreover, there is some evidence for similar behaviour in the  $b$ - and  $s$ -quark sectors.

As a summary, we list in Table 1 the states discussed above together with some of their pertinent properties.

Table 1: A summary of the properties of the candidate  $XYZ$  mesons discussed in the text. For simplicity, the quoted errors are quadratic sums of statistical and systematic uncertainties.

state	$M$ (MeV)	$\Gamma$ (MeV)	$J^{PC}$	Decay Modes	Production Modes
$Y_s(2175)$	$2175 \pm 8$	$58 \pm 26$	$1^{--}$	$\phi f_0(980)$	$e^+e^-$ (ISR), $J/\psi$ decay
$X(3872)$	$3871.4 \pm 0.6$	$< 2.3$	$1^{++}$	$\pi^+\pi^- J/\psi, \gamma J/\psi$	$B \rightarrow KX(3872), p\bar{p}$
$X(3875)$	$3875.5 \pm 1.5$	$3.0^{+2.1}_{-1.7}$		$D^0\bar{D}^0\pi^0$	$B \rightarrow KX(3875)$
$Z(3940)$	$3929 \pm 5$	$29 \pm 10$	$2^{++}$	$D\bar{D}$	$\gamma\gamma$
$X(3940)$	$3942 \pm 9$	$37 \pm 17$	$J^{P+}$	$D\bar{D}^*$	$e^+e^- \rightarrow J/\psi X(3940)$
$Y(3940)$	$3943 \pm 17$	$87 \pm 34$	$J^{P+}$	$\omega J/\psi$	$B \rightarrow KY(3940)$
$Y(4008)$	$4008^{+82}_{-49}$	$226^{+97}_{-80}$	$1^{--}$	$\pi^+\pi^- J/\psi$	$e^+e^-$ (ISR)
$X(4160)$	$4156 \pm 29$	$139^{+113}_{-65}$	$J^{P+}$	$D^*\bar{D}^*$	$e^+e^- \rightarrow J/\psi X(4160)$
$Y(4260)$	$4264 \pm 12$	$83 \pm 22$	$1^{--}$	$\pi^+\pi^- J/\psi$	$e^+e^-$ (ISR)
$Y(4350)$	$4361 \pm 13$	$74 \pm 18$	$1^{--}$	$\pi^+\pi^- \psi'$	$e^+e^-$ (ISR)
$Z(4430)$	$4433 \pm 5$	$45^{+35}_{-18}$	?	$\pi^\pm \psi'$	$B \rightarrow KZ^\pm(4430)$
$Y(4660)$	$4664 \pm 12$	$48 \pm 15$	$1^{--}$	$\pi^+\pi^- \psi'$	$e^+e^-$ (ISR)
$Y_b$	$\sim 10,870$	?	$1^{--}$	$\pi^+\pi^- \Upsilon(nS)$	$e^+e^-$

#### Summary points

1. QCD-motivated quark potential models describe the properties of the charmonium spectrum quite well.

2. In the last few years the  $\eta'_c$ ,  $h_c$  and  $\chi'_{c2}$  charmonium states have been discovered and their measured properties are in good agreement with the quark model predictions.
3. There is accumulating evidence for the existence of mesons with mass in the region between 3800 MeV/ $c^2$  and 4700 MeV/ $c^2$  that are not easily explained as simple quark-antiquark states of the charmonium model. These mesons have a number of intriguing and/or unexpected properties.
4. These states are relatively narrow although many of them are well above relevant open-charm thresholds. Many of them have partial widths for decays to charmonium + light hadrons that are at the  $\sim$ MeV scale, which is much larger than is typical for established  $c\bar{c}$  charmonium meson states.
5. The  $X(3872)$ , first seen as a narrow peak in the invariant mass distribution of  $\pi^+\pi^-J/\psi$  in  $B^- \rightarrow K^-\pi^+\pi^-J/\psi$ , is not easily described as a conventional  $c\bar{c}$  state and is a strong candidate for a  $D\bar{D}^*$  molecule.
6. The new  $1^{--}$  charmonium states are not apparent in the  $e^+e^- \rightarrow$  charmed-meson-pair or the total hadronic cross sections and there are no evident changes in the properties of these states at the  $DD^{**}$  mass threshold. There seems to be some selectivity: states seen to decay to final states with a  $\psi'$  are not seen in the corresponding  $J/\psi$  channel, and *vice versa*. At least one of these states is regarded as a strong candidate for a charmonium hybrid.
7. At least one of these new states, the  $Z(4430)$ , is unique in that it has a non-zero electric charge.
8. There is some evidence that similar states exist in the  $s$ - and  $b$ -quark sectors.

### Future issues

1. To confirm that these states are not conventional  $c\bar{c}$  states, more detailed studies of their properties, in particular, measurements of their quantum numbers and measurements of other decay modes, are required.
2. It will also be important to put rigorous quantitative limits on the non-observation of final states.
3. The existence of similar states in the  $s\bar{s}$  and  $b\bar{b}$  sectors should be verified and their properties measured.
4. Because many of these states have been observed to have masses that are close to kinematic thresholds it is necessary that we improve the theoretical understanding of threshold effects, including  $\pi$ -exchange contributions, coupled channel effects, and the interaction between both resonances and thresholds via coupled channel effects and the resulting observed cross sections.

### Acknowledgements

We thank T. Barnes, K.-F. Chen, S.-K. Choi, F. Close, E. Swanson, K. Trabelsi, S. Uehara and C.Z. Yuan for helpful communications. This work was supported

in part the Natural Sciences and Engineering Research Council of Canada, the U.S. Department of Energy and the Chinese Academy of Sciences.

## LITERATURE CITED

1. Gell-Mann M. 1964. A schematic model of baryons and mesons. *Phys. Rev. Lett.* 8:214–2
2. Zweig G 1964. An SU(3) model for strong interaction symmetry and its breaking. CERN Preprint 8182/TH401: 24.
3. Bali G S. 2001. QCD forces and heavy quark bound states. *Phys. Rept.* 343:1.
4. Eichten E, Godfrey S, Mahlke H, Rosner JL. 2007. Quarkonia and their transitions. arXiv:hep-ph/0701208.
5. Swanson ES. 2006. The new heavy mesons: A status report. *Phys. Rept.* 429:243–305.
6. Godfrey S. 2006. The XYZ's of c anti-c: Hints of exotic new mesons. *Proceedings of 4th Flavor Physics and CP Violation Conference (FPCP 2006), Vancouver, British Columbia, Canada, 9-12 Apr 2006* 015.
7. Zhu SL. 2007. New hadron states. arXiv:hep-ph/0703225.
8. Voloshin MB, Okun LB. 1976. Hadron Molecules And Charmonium Atom. *JETP Lett.* 23:333–336.
9. De Rujula A, Georgi H, Glashow SL. 1977. Molecular Charmonium: A New Spectroscopy?. *Phys. Rev. Lett.* 38:317–321.
10. Buchmuller W, Tye SHH. 1980. Vibrational States In The Upsilon Spectroscopy. *Phys. Rev. Lett.* 44:850–853.
11. Godfrey S, Napolitano J. 1999. Light meson spectroscopy. *Rev. Mod. Phys.* 71:1411–1462.
12. Rosner JL *et al.* (CLEO Collaboration) 2005. Observation of the  $h_c(^1P_1)$  state of charmonium. *Phys. Rev. Lett.* 95:102003–5
13. Dudek JJ. 2007. Charmonium from Lattice QCD. arXiv:0711.1600 [hep-ph].
14. Koma M, Koma Y, Wittig H. 2006. Determination of the spin-dependent potentials with the multi-level algorithm. *PoS LAT2005*:216. [arXiv:hep-lat/0510059].
15. Barnes T, Godfrey S, Swanson ES. 2005. Higher charmonia. *Phys. Rev. D* 72:054026.
16. Barnes T, Godfrey S. 2004. Charmonium options for the X(3872). *Phys. Rev. D* 69:054008.
17. Eichten EJ, Lane K, Quigg C. 2004. Charmonium levels near threshold and the narrow state  $X(3872) \rightarrow \pi^+\pi^-$ . *Phys. Rev. D* 69:094019.
18. Eichten EJ, Lane K, Quigg C. 2006. New states above charm threshold. *Phys. Rev. D* 73:014014. Erratum. 2006. *Phys. Rev. D* 73:079903.
19. Eichten EJ, Lane K, Quigg C. 2002. B meson gateways to missing charmonium levels. *Phys. Rev. Lett.* 89:162002.
20. Gottfried K. 1978. Hadronic Transitions between Quark-Antiquark Bound States. *Phys. Rev. Lett.* 40:598–601.
21. Bhanot G, Fischler W, Rudaz S. 1979. A Multipole Expansion And The Casimir-Polder Effect In Quantum Chromodynamics. *Nucl. Phys. B* 155:208–236.
22. Peskin ME. 1979. Short Distance Analysis for Heavy Quark Systems. 1. Diagrammatics. *Nucl. Phys. B* 156:365–390.

23. Bhanot G, Peskin ME. 1979. Short Distance Analysis for Heavy Quark Systems. 2. Applications. *Nucl. Phys. B* 156:391–416.
24. Voloshin MB. 1979. On Dynamics of Heavy Quarks in Nonperturbative QCD Vacuum. *Nucl. Phys. B* 154:365–380.
25. Yan TM. 1980. Hadronic Transitions Between Heavy Quark States In Quantum *Phys. Rev. D* 22:1652.
26. Kuang YP, Yan TM. 1980. Predictions For Hadronic Transitions In The B Anti-B System. *Phys. Rev. D* 24:2874–2885.
27. Voloshin MB. 2006. Two-pion transitions in quarkonium revisited. *Phys. Rev. D* 74:054022.
28. Voloshin MB. 1986. Hadronic Transitions From Upsilon (3s) to 1 P Wave Singlet Bottomonium Level. *Sov. J. Nucl. Phys.* 43:1011.
29. Kuang YP, Tuan SF, Yan TM. 1988. Hadronic Transitions And P Wave Singlet States Of Heavy Quarkonia. *Phys. Rev. D* 37:1210–1219.
30. Kuang YP, Yan TM. 1990. Hadronic transitions of D-wave quarkonium and  $\psi(3770) \rightarrow J/\psi\pi\pi$ . *Phys. Rev. D* 41:155–160.
31. Kuang YP. 2002.  $S - D$  mixing and searching for the  $\psi(1^1P_1)$  state at BEPC. *Phys. Rev. D* 65:094024.
32. Voloshin MB. 2003. The enhancement of the decay  $\Upsilon(1D) \rightarrow \eta\Upsilon(1S)$  by the axial anomaly in QCD. *Phys. Lett. B* 562:68–74.
33. Kuang YP. 2006 QCD multipole expansion and hadronic transitions in heavy quarkonium systems. *Front. Phys. China* 1:19–37.
34. Micu L. 1969. Decay Rates Of Meson Resonances In A Quark Model. *Nucl. Phys. B* 10:521.
35. Le Yaouanc A, Oliver L, Pène O, Raynal JC. 1973. Naive Quark Pair Creation Model Of Strong Interaction Vertices. *Phys. Rev. D* 8:2223.
36. Kwong W, Mackenzie PB, Rosenfeld R, Rosner JL. 1988. Quarkonium Annihilation Rates. *Phys. Rev. D* 37:3210–3215.
37. Petrelli A, Cacciari M, Greco M, Maltoni F, Mangano ML. 1998. NLO production and decay of quarkonium, *Nucl. Phys. B* 514:245–309.
38. Tornqvist NA, 1994. From the deuteron to deusons, an analysis of deuteron-like meson meson bound states. *Z. Phys. C* 61:525–18
39. Ericson TEO, Karl G. 1993. Strength of pion exchange in hadronic molecules. *Phys. Lett. B* 309:426.
40. Maiani L, Piccinini F, Polosa AD, Riquer V. 2005. Diquark-antidiquarks with hidden or open charm and the nature of X(3872). *Phys. Rev. D* 71:014028.
41. Chiu T-W, Hsieh TH. 2006 Pseudovector meson with strangeness and closed charm. *Phys. Rev. D* 73:111503(R)–4.
42. Barnes T, Close FE, Swanson ES. 1995. Hybrid and conventional mesons in the flux tube model: Numerical studies and their phenomenological implications. *Phys. Rev. D* 52:5242–5256.
43. Morningstar C. 2000. Hybrid mesons from lattice QCD. *Nucl. Phys. Proc. Suppl.* 90:214–218.
44. Bali GS, Pineda A. 2004. QCD phenomenology of static sources and gluonic excitations at short distances. *Phys. Rev. D* 69:094001.
45. Isgur N, Paton JE. 1985. A Flux Tube Model For Hadrons In QCD. *Phys. Rev. D* 31:2910–2929.
46. Lacock P, Michael C, Boyle P, Rowland P [UKQCD Collaboration] 1997. Hybrid mesons from quenched QCD. *Phys. Lett. B* 401:308.
47. McNeile C, Michael C, Pennanen P (UKQCD Collaboration) 2002. Hybrid



- meson decay from the lattice. *Phys. Rev. D* 65:094505.
48. Close F. 2008. Three flavours of Hybrid or  $\pi$  exchange: which is more attractive? arXiv:0801.2646 [hep-ph].
  49. Voloshin MB. 2006. Channel coupling in  $e^+e^-$  annihilation into heavy meson pairs at the  $D^*\bar{D}^*$  threshold. arXiv:hep-ph/0602233.
  50. Eichten E, *et al.* 1976. The Interplay Of Confinement And Decay In The Spectrum Of Charmonium. *Phys. Rev. Lett.* 36:500.
  51. Eichten E, *et al.* 1978. Charmonium: The Model. *Phys. Rev. D* 17:3090. [Erratum 1980 *ibid.* *Phys. Rev. D* 21:313].
  52. Eichten E, *et al.* 1980. Charmonium: Comparison With Experiment. *Phys. Rev. D* 21:203.
  53. Aubert B *et al.* (BaBar Collaboration) 2001. Observation of CP violation in the  $B^0$  meson system. *Phys. Rev. Lett.* 87: 091801–7
  54. Abe K *et al.* (Belle Collaboration) 2001. Observation of a large CP violation in the neutral  $B$  meson system. *Phys. Rev. Lett.* 87:091802–7
  55. Choi S-K *et al.* (Belle Collaboration) 2002. Observation of the  $\eta_c(2S)$  in exclusive  $B \rightarrow KK_S K^- \pi^+$  decays. *Phys. Rev. Lett.* 89:102001–5
  56. Aubert B *et al.* (BaBar Collaboration) 2004. Study of the  $e^+e^- \rightarrow \pi^+\pi^-\pi^0$  process using initial state radiation with BaBar. *Phys. Rev. D* 70: 072004–22
  57. Abe K *et al.* (Belle Collaboration) 2002. Observation of double  $c\bar{c}$  production in  $e^+e^-$  annihilation at  $\sqrt{s} \simeq 10.6$  GeV. *Phys. Rev. Lett.* 89:142001–6
  58. Braaten E, Fleming S 1995. Color-octet fragmentation and the  $\psi'$  excess at the Fermilab Tevatron. *Phys. Rev. Lett.* 74:3327–4
  59. Asner D *et al.* (CLEO Collaboration) 2004. Observation of  $\eta'_c$  production in  $\gamma\gamma$  fusion at CLEO. *Phys. Rev. Lett.* 92:142001–5
  60. Choi S-K *et al.* (Belle Collaboration) 2003. Observation of a narrow charmoniumlike state in exclusive  $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$  decay. *Phys. Rev. Lett.* 91:262001–6
  61. Acosta D *et al.* (CDF Collaboration) 2004. Observation of the narrow state  $X(3872) \rightarrow J/\psi \pi^+ \pi^-$  in  $\bar{p}p$  collisions at  $\sqrt{s} = 1.96$  TeV. *Phys. Rev. Lett.* 93:072001–6
  62. Abazov VM *et al.* (D0 Collaboration) 2004. Observation and properties of the  $X(3872)$  decaying to  $\pi^+ \pi^- \psi$  in  $\bar{p}p$  collisions at  $\sqrt{s} = 1.96$  TeV. *Phys. Rev. Lett.* 93:162002–6
  63. Aubert B *et al.* (BaBar Collaboration) 2005. Study of the  $B^- \rightarrow J/\psi K^- \pi^+ \pi^-$  decay and measurement of the  $B^- \rightarrow X(3872) K^-$  branching fraction. *Phys. Rev. D* 71: 071103–7
  64. Yao WM *et al.* (Particle Data Group) 2007. Review of particle physics. *J. Phys. G* 33: 1–1232
  65. Aubert B *et al.* (BaBar Collaboration) 2006. Search for  $B^+ \rightarrow X(3872) K^+$ ,  $X(3872) \rightarrow J/\psi \gamma$ . *Phys. Rev. D* 74:071101.
  66. Abe K *et al.* (Belle Collaboration) 2005. Belle report BELLE-CONF-0540, arXiv:hep-ex/0505037, paper no. LP-2005-175, contributed to the *XXII International Symposium on Lepton-Photon Interactions at High Energy*, Uppsala, Sweden, June 30 – July 5, 2005.
  67. Abulencia D *et al.* (CDF Collaboration) 2006. Measurement of the dipion mass spectrum in  $X(3872) \rightarrow J/\psi \pi^+ \pi^-$  decays. *Phys. Rev. Lett.* 96:102002–7
  68. Swanson ES. 2004. Short range structure in the  $X(3872)$ . *Phys. Lett. B* 588:189–195.
  69. Close FE, Page PR. 2004. The  $D^{*0}\bar{D}^0$  threshold resonance. *Phys. Lett. B*

- 578:119–123.
70. Abulencia D *et al.* (CDF Collaboration) 2007. Analysis of the quantum numbers  $J^{PC}$  of the  $X(3872)$  particle. *Phys. Rev. Lett.* 98:132002–7
  71. Cawfield C *et al.* (CLEO Collaboration) 2007. Precision determination of the  $D^0$  mass. *Phys. Rev. Lett.* 98:092002–5
  72. Voloshin MB. 2004. Interference and binding effects in decays of possible molecular component of  $X(3872)$ . *Phys. Lett. B* 579:316–320.
  73. Gamermann D, Oset E. 2007. Axial Resonances in the Open and Hidden Charm Sectors. *Eur. Phys. J. A* 33:119.
  74. Ebert D, Faustov RN, Galkin VO. 2006. Masses of heavy tetraquarks in the relativistic quark model, *Phys. Lett. B* 634:214–219.
  75. Abe K *et al.* (Belle Collaboration), 2007. Study of  $B \rightarrow X(J/\psi\pi^+\pi^-)K$  decays. Belle-CONF-0711
  76. Aubert B *et al.* (BaBar Collaboration) 2006. Study of the  $X(3872)$  and  $Y(4260)$  in  $B^0 \rightarrow J/\psi\pi^+\pi^-K^0$  and  $B^- \rightarrow J/\psi\pi^+\pi^-K^-$  decays. *Phys. Rev. D* 73:011101(R)–7.
  77. Aubert B *et al.* (BaBar Collaboration) 2007. Search for a charged of the  $X(3872)$  in the  $B$  meson decay  $B^- \rightarrow X^-K$ ,  $X^- \rightarrow J/\psi\pi^-\pi^0$ . *Phys. Rev. D* 71:031501(R)–8.
  78. Gokhroo G *et al.* (Belle Collaboration) 2006. Observation of a near-threshold  $D^0\bar{D}^0\pi^0$  enhancement in  $B \rightarrow D^0\bar{D}^0\pi^0K$  decay. *Phys. Rev. Lett.* 97:162002–6
  79. Aubert B *et al.* (BaBar Collaboration) 2007. Study of resonances in exclusive  $B$  decays to  $\bar{D}^{(*)}D^{(*)}K$ . arXiv:0708.1565, submitted to *Phys. Rev. D*–8
  80. Dunwoodie W, Ziegler V. 2007. A Simple Explanation for the  $X(3872)$  Mass Shift Observed for Decay to  $D^{*0}\bar{D}^0$ . arXiv:0710.5191.
  81. Hanhart C, Kalashnikova YuS, Kudryavtsev AE, Nefediev AV. 2007. Reconciling the  $X(3872)$  with the near-threshold enhancement in the  $D^0\bar{D}^{*0}$  final state. *Phys. Rev. D* 76:014007–9
  82. Voloshin MB. 2007. Isospin properties of the  $X$  state near the  $D\bar{D}^*$  threshold. *Phys. Rev. D* 76:014007.
  83. Braaten E, Lu M. 2007. The Effects of Charged Charm Mesons on the Line Shapes of the  $X(3872)$ . arXiv:0710.5482 [hep-ph].
  84. Abe K *et al.* (Belle Collaboration) 2007. Observation of a charmoniumlike state produced in association with a  $J/\psi$  in  $e^+e^-$  annihilations near  $\sqrt{s} \simeq 10.6$  GeV. *Phys. Rev. Lett.* 98:082001–6
  85. Choi S-K *et al.* (Belle Collaboration) 2005. Observation of a near-threshold  $\omega J/\psi$  mass enhancement in exclusive  $B \rightarrow K\omega J/\psi$  decays. *Phys. Rev. Lett.* 94:182002–6
  86. Uehara S *et al.* (Belle Collaboration) 2006. Observation of a  $\chi'_{c2}$  candidate in  $\gamma\gamma \rightarrow D\bar{D}$  production at Belle. *Phys. Rev. Lett.* 96:082003–6
  87. Swanson E. 2006. Review of heavy hadron spectroscopy. *Int. J. Mod. Phys. A* 21:733–738.
  88. Barnes T. 1992. Two photon couplings of quarkonia with arbitrary  $J(PC)$ . Invited paper at *Int. Workshop on Photon-Photon Collisions, La Jolla, CA, March 22 – 26, 1992*. Oak Ridge National Laboratory Report No. ORNL-CCIP-92-05.
  89. Adachi I *et al.* (Belle Collaboration) 2007. Production of new charmonium-like states in  $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^{(*)}$  at  $\sqrt{s} \simeq 10.6$  GeV. arXiv:0708.3812v2, submitted to *Physical Review Letters*

90. Barnes T, Godfrey S, Swanson ES, 2005. Higher Charmonium. *Phys. Rev. D* 72:054026–20
91. Aubert B *et al.* (BaBar Collaboration) 2005. Observation of  $Y(3940) \rightarrow J/\psi\omega$  in  $B \rightarrow J/\psi\omega K$  at BaBar. arXiv:0711.2047, submitted to *Physical Review Letters*.
92. Barnes T. 2006. The XYZs of charmonium at BES, *Int. J. Mod. Phys. A* 21:5583–5591.
93. Godfrey S, Isgur N. 1985. Mesons In A Relativized Quark Model With Chromodynamics. *Phys. Rev. D* 32:189–231.
94. Aubert B *et al.* (BaBar Collaboration) 2005. Observation of a broad structure in the  $\pi^+\pi^-J/\psi$  mass spectrum around  $4.26 \text{ GeV}/c^2$ . *Phys. Rev. Lett.* 95:142001–7
95. Pakhlova G *et al.* (Belle Collaboration) 2007. Measurement of the near-threshold  $e^+e^- \rightarrow D^{(*)\pm}D^{(*)\mp}$  cross section via initial-state radiation. *Phys. Rev. Lett.* 98:092001–5
96. Bai JZ *et al.* (BES Collaboration) 2002. Measurement of the cross section for  $e^+e^- \rightarrow$  hadrons at center-of-mass energies from 2 to 5 GeV. initial state radiation. *Phys. Rev. Lett.* 88:101802–5
97. Wang XL, Li G, Yuan CZ, Hu HM, Hu JH, Wang P, Wang ZY 2007. Determining the upper limit of  $\Gamma_{ee}$  for the  $Y(4260)$ . *Phys. Lett. B* 640:182–7
98. He Q *et al.* (CLEO Collaboration) 2006. Confirmation of the  $Y(4260)$  resonance production in initial state radiation. *Phys. Rev. D* 74:091104(R)–5
99. Yuan CZ *et al.* (Belle Collaboration) 2007. Measurement of the  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  crosssection via initial state radiation. *Phys. Rev. Lett.* 99:182004–6
100. Aubert B *et al.* (BaBar Collaboration) 2007. Evidence of a broad structure at an invariant mass of  $4.32 \text{ GeV}/c^2$  in the reaction  $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ . *Phys. Rev. Lett.* 98:212001–7
101. Wang XL *et al.* (Belle Collaboration) 2007. Observation of two resonant structures in  $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$  via initial state radiation. *Phys. Rev. Lett.* 99:142002–5
102. Ding GJ, Zhu JJ, Yan ML. 2007. Canonical Charmonium Interpretation for  $Y(4360)$  and  $Y(4660)$ . arXiv:0708.3712 [hep-ph].
103. Liu X. 2007. Understanding the newly observed  $Y(4008)$  by Belle. arXiv:0708.4167 [hep-ph].
104. Rosner JL. 2006. Effects of S-wave thresholds. *Phys. Rev. D* 74:076006.
105. Swanson E. 2006. Review of heavy hadron spectroscopy. *Int. J. Mod. Phys. A* 21:733. [arXiv:hep-ph/0509327].
106. Rosner JL. 2007. Heavy quark spectroscopy: Theory overview. *J. Phys. Conf. Ser.* 69:012002.
107. Close FE. 2007. Rumsfeld Hadrons. In *the Proceedings of 5th Flavor Physics and CP Violation Conference (FPCP 2007), Bled, Slovenia, 12-16 May 2007, pp 020* [arXiv:0706.2709 [hep-ph]].
108. Maiani L, Riquer V, Piccinini F, Polosa AD. 2005. Four quark interpretation of  $Y(4260)$ . *Phys. Rev. D* 72:031502.
109. Zhu SL. 2005. The Possible interpretations of  $Y(4260)$ . *Phys. Lett. B* 625:212–216.
110. Close FE, Page PR. 2005. Gluonic charmonium resonances at BaBar and Belle? *Phys. Lett. B* 628:215–222.
111. Kou E, Pène O. 2005. Suppressed decay into open charm for the  $Y(4260)$

- being an hybrid. *Phys. Lett. B* 631:164–169.
112. Ablikim M *et al.* (BES Collaboration). 2007. Determination of the  $\psi(3770)$ ,  $\psi(4040)$ ,  $\psi(4160)$  and  $\psi(4415)$  resonance parameters. arXiv:0705.4500 [hep-ex].
  113. Choi S-K *et al.* (Belle Collaboration) 2007. Observation of a resonance-like structure in the  $\pi^\pm\psi'$  mass distribution in exclusive  $B \rightarrow K\pi^\pm\psi'$  decays. arXiv:0708.1790v2, submitted to *Physical Review Letters*
  114. Rosner JL. 2007. Threshold effect and  $\pi^\pm\psi(2S)$  peak. *Phys. Lett. D* 76:114002.
  115. Meng C, Chao KT. 2007.  $Z^+(4430)$  as a resonance in the  $D_1(D_1')D^*$  channel. arXiv:0708.4222 [hep-ph].
  116. Lee, SH, Mihara A, Navarra FS, Nielsen M. 2007. QCD sum rules study of the meson  $Z^+(4430)$ . arXiv:0710.1029 [hep-ph].
  117. Liu X, Liu YR, Deng WZ, Zhu SL, 2007. Is  $Z^+(4430)$  a loosely bound molecular state?. arXiv:0711.0494 [hep-ph].
  118. Maiani L, Polosa AD, Riquer V. 2007. The Charged  $Z(4433)$ : Towards a New Spectroscopy. arXiv:0708.3997 [hep-ph].
  119. Ding GJ, 2007. Understanding the Charged Meson  $Z(4430)$ . arXiv:0711.1485 [hep-ph].
  120. Cheung KM, Keung WY, Yuan TC. 2007. Bottomed Analog of  $Z^+(4433)$ . arXiv:0709.1312 [hep-ph].
  121. Aubert B *et al.* (BaBar Collaboration) 2006. Observation of  $\Upsilon(4S)$  decays to  $\pi^+\pi^-\Upsilon(1S)$  and  $\pi^+\pi^-\Upsilon(2S)$ . *Phys. Rev. Lett.* 96:232001–7
  122. Sokolov A *et al.* (Belle Collaboration) 2007. Observation of the decay  $\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ . *Phys. Rev. D* 75:071103–6
  123. Chen KF *et al.* (Belle Collaboration) 2007. Observation of anomalous  $\pi^+\pi^-\Upsilon(1S)$  and  $\pi^+\pi^-\Upsilon(2S)$  production at  $\sqrt{s} \simeq 10.87$  GeV. arXiv:0710.2577, submitted to *Physical Review Letters*
  124. Hou W-S 2007 Searching for the bottom counterparts of  $X(3872)$  and  $Y(3940)$  via  $\pi^+\pi^-\Upsilon$ . *Phys. Rev. D* 74:017504–4
  125. Aubert B *et al.* (BaBar Collaboration) 2006. Structure at 2175 MeV in  $e^+e^- \rightarrow \phi f_0(980)$  observed via initial state radiation. *Phys. Rev. D* 74: 091103–9
  126. Ablikim M *et al.* (BES Collaboration) 2007. Observation of  $Y(2175)$  in  $J/\psi \rightarrow \eta\phi f_0(980)$ . arXiv:0712.1143, submitted to *Physical Review Letters*
  127. Ding G-J, Yan M-L. 2007. A candidate for  $1^{--}$  strangeonium hybrid. *Phys. Lett. B* 650: 390–400.
  128. Ding GJ, Yan ML. 2007.  $Y(2175)$ : Distinguish hybrid state from higher quarkonium. *Phys. Lett. B* 657:49–54.